

1995/20 455

9

RECURRENT NOVAE

M. Hack and P. L. Selvelli

I. THE KNOWN RECURRENT NOVAE

Recurrent novae seem to be a rather inhomogeneous group: T CrB is a binary with a M III companion; U Sco probably has a late dwarf as companion. Three are fast novae; two are slow novae. Some of them appear to have normal chemical composition; others may present He and CNO excess. Some present a mass-loss that is lower by two orders of magnitude than classical novae. However, our sample is too small for saying whether there are several classes of recurrent novae, which may be related to the various classes of classical novae, or whether the low mass-loss is a general prop-

erty of the class or just a peculiarity of one member of the larger class of classical novae and recurrent novae.

Five recurrent novae have been observed up to now (Table 9.1).

It is an open problem whether the well known relation between amplitude and cycle length existing for dwarf novae may be extended to recurrent novae, especially since the gap existing between the greatest cycle length

TABLE 9-1. KNOWN RECURRENT NOVAE

Name	Epochs of outbursts	Apparent magnitudes Min - Max	Light Curve Class	Spectrum (quiescence)	Notes
U Sco	1863,1906, 1936,1979, 1987	19.2v-8.8v	Fast	GO V	
T Pyx	1890,1902, 1920,1944, 1966	15.3p-6.5p	Slow	Very blue	
RS Oph	1898,1933, 1958,1967, 1985	12.5v-4.3v	Fast	M III	
V1017Sgr	1901,1919 1973	14.7B-7.2p	Slow	G5 IIIp	Symbiotic?
T CrB	1866,1946	11.3p-2.0p	Fast	M3 III	Sp.bin P = 227.3d

in dwarf novae* (about 1.5 years) and the smallest one in recurrent novae (about 20 years) has been filled by WZ Sge, of which the outburst properties are typical of dwarf novae, but which has a cycle length of about 33 years, and by the recurrent nova RS Oph which has outburst properties typical of a nova, but which has exhibited outbursts at intervals less than 10 years.

A recent compilation of amplitudes A and cycle lengths C for dwarf novae and recurrent

novae, including three X-ray recurrent novae, has produced the graph published by Richter (1986) (Figure 9-1).

This superposition in cycle length has posed some problems in defining recurrent novae. Webbink et al. (1987) give the following criteria for defining a recurrent nova unambiguously:

- 1) Two or more recorded outbursts, reaching absolute magnitude at maximum compa-

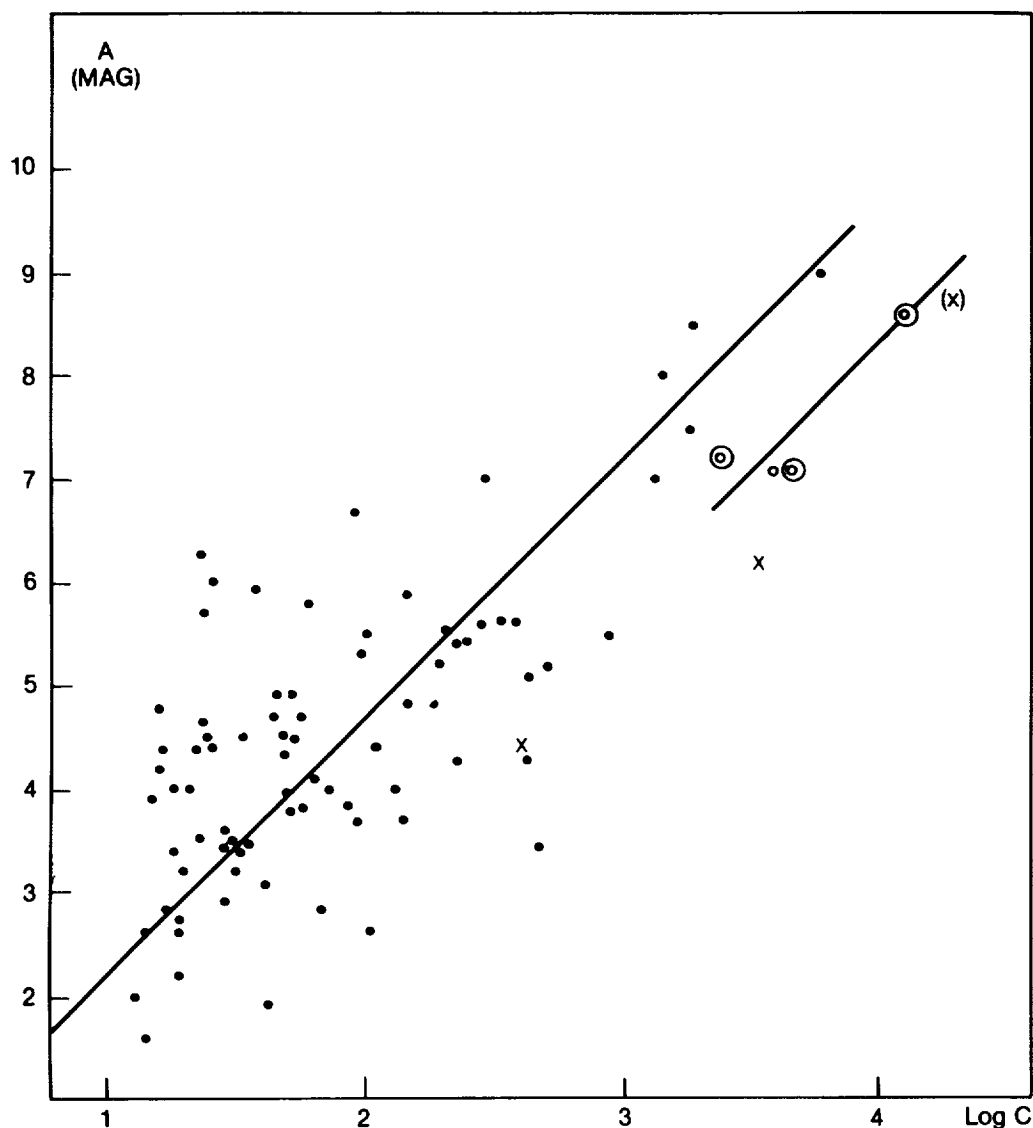


Figure 9-1. Amplitude-Cycle length relationship of cataclysmic variables. Dots: dwarf novae; circles: recurrent novae; crosses: recurrent X-ray novae. Very uncertain values are in brackets. (from Richter, 1986).

*See also Chapter 2, II.A.3 on Dwarf Novae. Actually, if we consider Dwarf Novae alone the scatter is very large.

table with those of classical novae (i.e., $M_V \leq -5.5$).

2) Ejection of a discrete shell in outburst, at velocities comparable with those of classical novae ($V_{\text{exp}} \geq 300 \text{ km/s}$).

The first criterion distinguishes recurrent novae from both classical and dwarf novae and also from symbiotic novae. The second distinguishes them from the remaining symbiotic stars, many of which show bright, multiple outbursts, but without high-velocity shell ejection.

We will report in detail the results of the observations of the five objects: U Sco, T Cr B, RS Oph, T Pyx, and V 1017 Sgr, and we will compare these objects among themselves, and with classical novae.

II. U SCO

The recurrent nova has undergone recorded outbursts in 1863, 1906, 1936, 1979, and another in 1987. At quiescence, it is very faint ($V = 19.2$) and reaches $V = 8.8$ at maximum. On May 5.55, 1987, V was equal to 15.5. There are no observations between May 10, when $V = 13$, and May 16.08 when $V = 10.8$ (see IAU Circular No. 4395 of May 18, 1987). It is, therefore, probable that the maximum of 8.8 was reached during this gap (on May 13.5, 1987 according to Rosino and Iijima, 1988). Five superposed visual light curves are shown in Figure 9-2 from their paper.

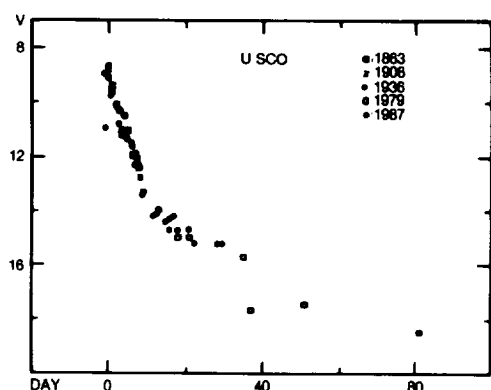


Figure 9-2. Five superposed visual light curves of U Sco.
(from Rosino and Iijima, 1988).

The light curve is typical of very fast nova, with $t_3 = 6\text{d}$ and with a smooth decline (Figure 9.2).

Two spectra taken during the 1987 outburst are shown by Rosino and Iijima (1988). The first one, obtained on May 22, is characterized by the presence of a relatively weak continuum and emission lines of H, He II, N III, N IV, N V, C III, C IV, Si III, Fe III, O IV, and O VI, indicating a very high degree of excitation. The second spectrum obtained about 24 hours later is similar to the first except for the drastic fading of the $\lambda 4640$ blend, which was very strong the night before.

Reports on the previous outbursts were given by Pogson (1908) and by Thomas (1940). A complete spectrophotometric study in the visual and ultraviolet range was made during the 1979 outburst by Barlow et al. (1981) and by Williams et al. (1981). Spectroscopic observations in the range accessible from the ground were obtained during the whole outburst. In addition, a preoutburst spectrum was taken on March 26, 1979 (Figure 9-3). The maximum brightness was reached on June 24, and an early outburst spectrum was obtained by Duerbeck and Seitter (1980) on June 28.95 U.T. The pre-outburst spectrum and one obtained on July 12, 1979, when the visual magnitude was about 15, are very similar. They do not present strong emission and absorption features, with the exception of the He II emission at 4686 Å, which is always dominant (see also the spectrum taken by Williams-Williams et al. 1981 in March 1980, Figure 9.7). On July 2 and 3, the strong He II emission shows a double-peaked profile; H Beta and H Gamma show a broad emission - full width at zero intensity (FWZI) $\approx 10000 \text{ km/s}$, and a narrow asymmetric feature, split in two to four components, separated by about 500 km/s, while the FWZI is 1600 km/s (Figure 9-4). A very broad strong emission feature is present on July 2 in the spectral interval 4500-4700 Å, and it diminishes rapidly in intensity. It is probably a blend of N III, N V, C III, C IV and He II emissions.

Such broad complex profiles of the Balmer emissions clearly indicate expansion velocities

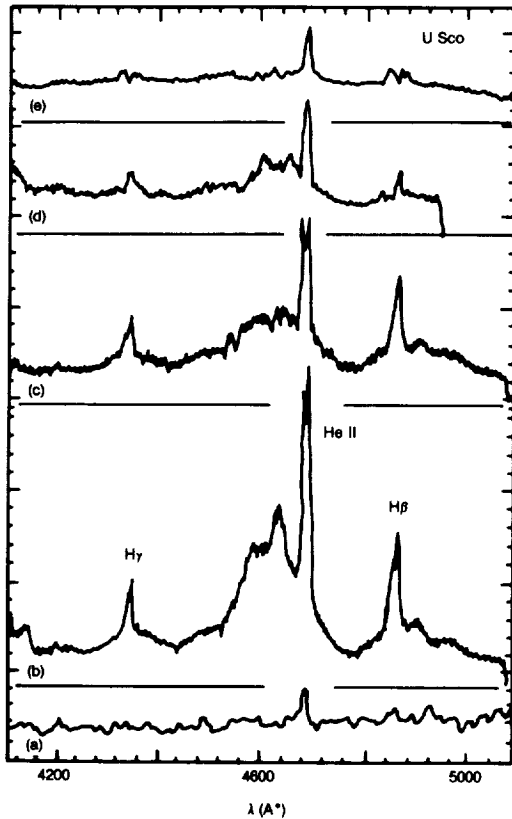


Figure 9-3. Early evolution of the spectrum of U Sco through the 1979 outburst. The dates, from bottom to top are: March 26, July 2, July 3, July 6 and July 12, 1979. (from Barlow et al., 1981).

of the ejecta as large as 5000 km/s, much larger than those usually found in classical novae, which rarely are larger than 2000 km/s (Figures 9.4 and 9.5). The expansion velocities indicated by the ultraviolet spectrum are much larger than the visual ones.

On August 13, U Sco had faded to magnitude 17. One absorption feature is observable at 5175 Å and can be attributed to the Mg I triplet at 5167-5183. Since this feature is dominant in spectral types later than G0, it is possible that it is due to a late-type underlying star (Figure 9.6). Another spectrum was obtained by Williams in March 1980 (Figure 9.7) when the star was back to its quiescent magnitude: it still shows the strong He II emission at 4686 Å. Two fainter but clearly detectable emissions at 5411 and 6560 are attributed to He II and to H + He II. 3781 and 4200 He II are also detectable. A nonidentified emission feature at 6250 is rather

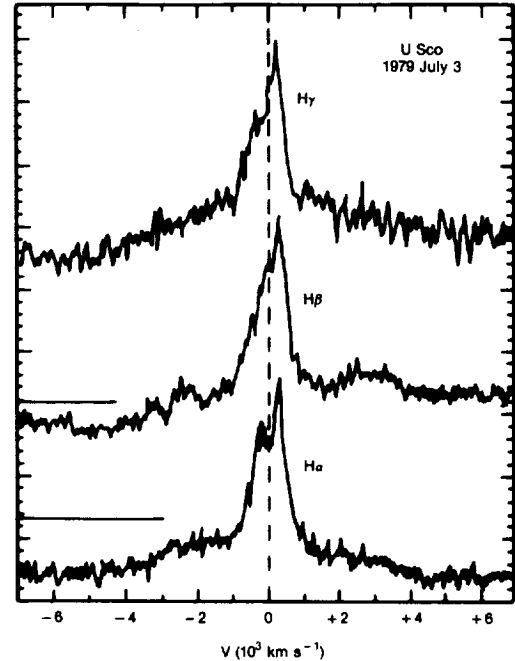


Figure 9-4. The profiles of the Balmer lines on July 3, 1979 plotted on velocity scale. (from Barlow et al., 1981)

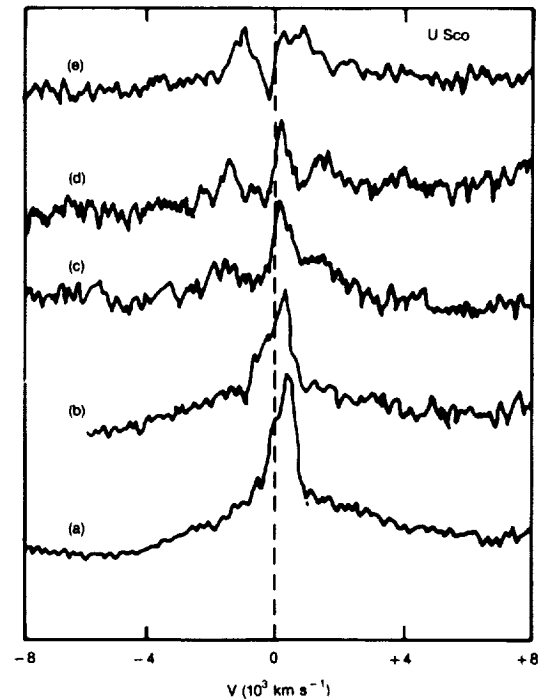


Figure 9-5. The H Gamma profile of U Sco at various epochs, plotted on velocity scale. The dates from the bottom to top are July 2, July 3, July 6, July 8 and July 12, 1979. (from Barlow et al., 1981).

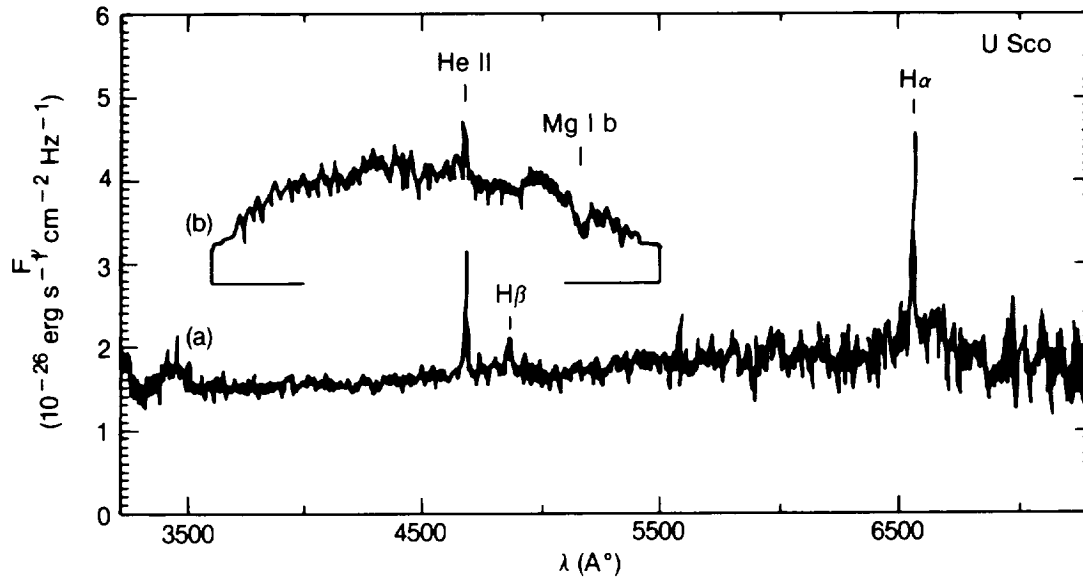


Figure 9-6. The spectrum of U Sco late in the outburst.
(from Barlow et al., 1981).

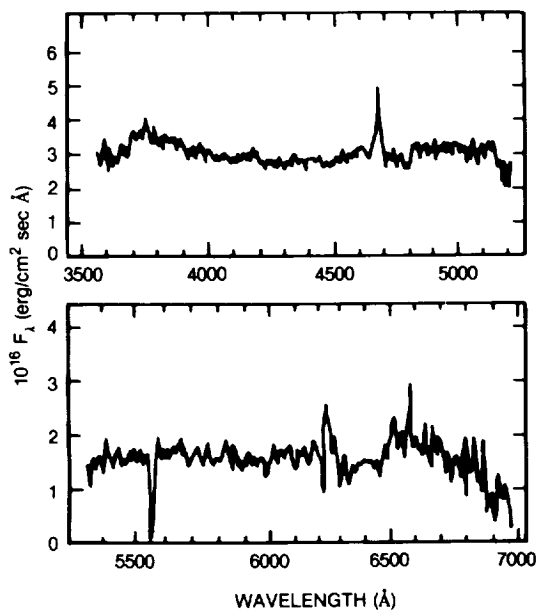


Figure 9-7. Optical spectrum of U Sco obtained in March 1980 after the nova had returned to quiescence.
(from Williams et al., 1981)

strong. There is no evidence for the presence of the Balmer lines. It is not possible to say whether some absorption lines are present. Another postoutburst spectrum was observed by Hanes (1985) in June 1982, with a resolution of about 8 Å, when the visual magnitude was about 17.85. The flux distribution observed in March 1979, about 3 months before outburst, and the observed in June 1982 are identical,

although in 1979, the star was about 2 magnitudes brighter (Figure 9-8). The line spectrum presents emission lines of He II 4200, 4542, 4686, and 5412 Å, the absorption lines H and K of Ca II and of the Mg I triplet at 5167, 5173, and 5184 Å, and a depression at the Balmer limit, which, however, cannot be attributed to H I since no Balmer lines are observable either in absorption or in emission (Figure 9.9-a). This depression is very probably due to a blend of metallic lines. This feature, together with the presence of the Mg I absorption triplet, and the comparison with the spectra of 70 Oph (K0V), Mu Ara (G5V) and 58 Oph (F7V) sug-

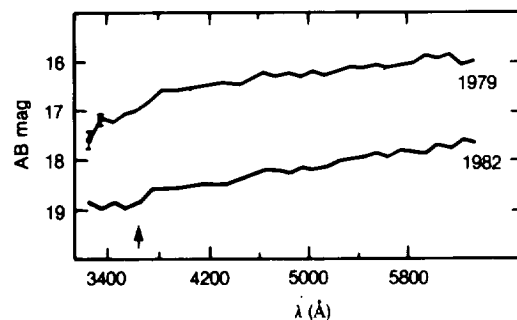


Figure 9-8. The flux distribution for U Sco in 1982 and 1979. The scale for the 1982 curve is AB Mag = $-2.5 \log f(\nu)$ - 48.60. The spectrum of 1979 has been arbitrarily shifted vertically. The arrow indicated the position of the Balmer discontinuity at 3636 Å.
(from Hanes, 1985).

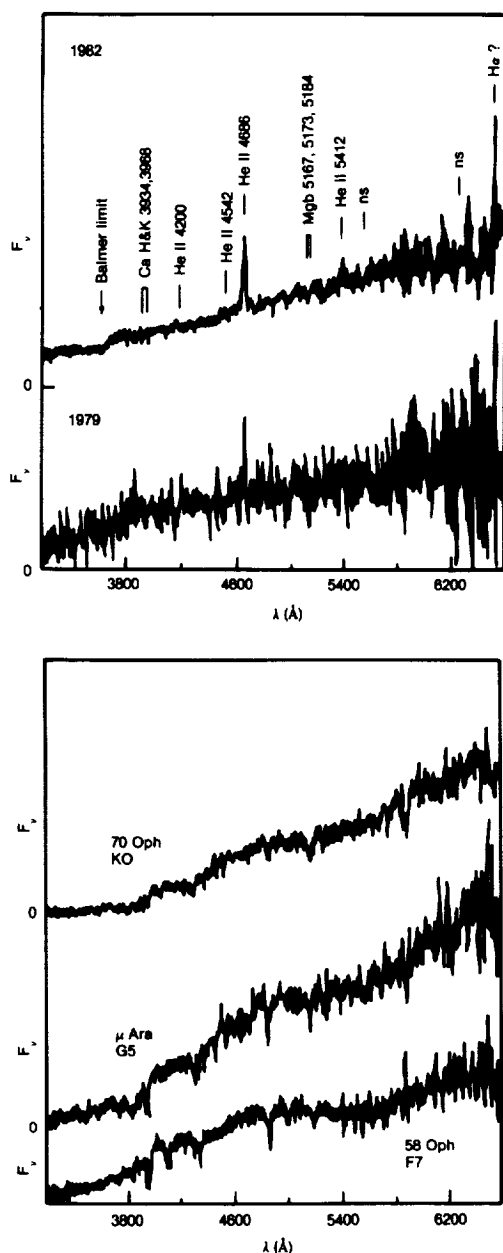


Figure 9-9. a) The narrow-slit spectrum of U Sco in 1982 obtained with an integration time of 14000 s. Below is shown the 1979 spectrum obtained with an integration time of 1000 s. The ordinate scale is in units of flux per unit frequency and is linear. The zero point for each spectrum is shown. b) The spectra of three main-sequence stars are shown. The spectra were obtained with the same instrumentation as for U Sco. The ordinate and abscissa scales are the same. The comparison of the spectrum of U Sco with those of the standard stars suggests a spectral type F7-GO. (from Hanes, 1985).

gest a spectral type G0 \pm 5 (Figure 9-9b). By plotting the infrared colors of U Sco in the two diagrams (H-K) vs (J-H) and (V-K) vs (J-H) and comparing the position of U Sco with those of main sequence stars, it appears that U Sco is a G0 or a late F main sequence star (Figure 9-10).

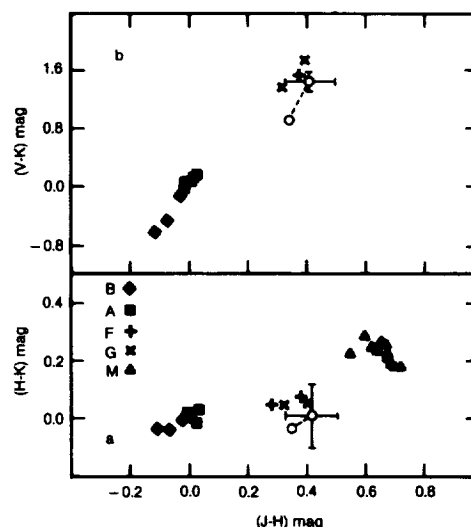


Figure 9-10. The position of U Sco (circle with error bars) in the (H-K), (J-K) two infrared color diagram is very close to that of F and G stars. (from Hanes, 1985).

II.A. ULTRAVIOLET OBSERVATIONS

Several far-ultraviolet, low-resolution spectra were also obtained with IUE during the 1979 outburst, mainly by Williams et al. (1981) plus one by Barlow et al. (1981) during the period June 28 to July 11, 1979. The main characteristic is the strong emission 1240 N V, which is much stronger than 1550 C IV. The latter presents a strong shortward absorption component on June 28, which is fainter on June 30 and absent on July 2. On June 28 also, low- or relatively low-ionization features, like C II or Si IV, are present, but they have disappeared by July 2 (see Figure 6-52).

Simultaneous observations of U Sco in the ultraviolet (1175-2000 Å) and in the visual range were obtained by Barlow et al (1981) on July 6. These observations permitted Barlow et al. to derive the energy distribution (Figure 9-11). However, no data for the near-ultraviolet

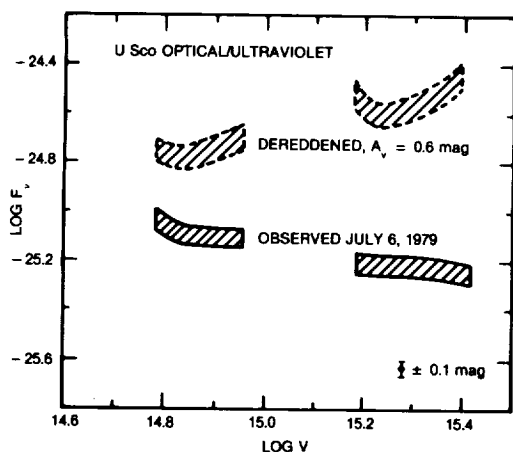


Figure 9-11. The observed continuum flux (in $\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$) of U Sco on July 6, 1979. (from Barlow et al., 1981).

were obtained that would allow a direct measurement of the interstellar reddening by means of the 2200 \AA feature.

An estimate of this was made by using the $1640 \text{ He II}/4686 \text{ He II}$ ratio, which is not very sensitive to either density or temperature. A value of $E(B-V) = 0.2$ and $A_v = 3.1 E(B-V) = 0.6$ was found. Figure 9-11 illustrates how strongly the energy distribution depends on the dereddening.

Other data obtained from June 26 to July 6 in the I-R-V-B-U bands show that the energy distribution remains remarkably constant from June 29 to July 6. This behavior is different from that of classical novae, which show a shift to the ultraviolet with time after maximum.

II.B. ABUNDANCES IN THE EJECTA

Abundances in the ejecta were derived from the visual (Barlow et al., 1981) and the ultraviolet (Williams et al., 1981) spectra. The presence of many strong lines of N III and N IV in the visual spectrum probably indicates an excess of nitrogen. The ratio H/He can be derived quantitatively by the ratio of the even to the odd members of the Pickering series. In fact, it is well known that the even members of the He II Pickering series are almost coincident with

the Balmer series. If we assume that the higher members of the series are optically thin, the fluxes are proportional to the numbers of the emitting ions: $F(\text{even})/F(\text{odd}) = (H^+ + \text{He}^{2+}) / \text{He}^{2+}$. By this method $H^+/\text{He}^{2+} = H^+/\text{He}^{2+} = H/\text{He} = 0.5$ is found.

The ultraviolet spectrum permits us to derive the H/He abundance from the ratio Ly Alpha/ 1640 He II with considerable accuracy, since the two lines are both formed by recombination and, hence, the ratio is not strongly dependent upon other parameters. A difficulty, however, is to disentangle the stellar Ly Alpha from the geocoronal Ly Alpha emission.

Relative abundances of carbon, nitrogen, and oxygen can be derived reliably, because all the ultraviolet lines of these ions are transitions from collisionally excited levels which, therefore, present the same dependence on temperature and density. By assuming that the ionization degrees of C, N, O are similar, i.e., that $C^{3+}/N^{3+} = C/N$ and $N^{2+}/O^{2+} = N/O$, then approximate abundance ratios can be derived by the ratios $1550 \text{ C IV}/1486 \text{ N IV}$, and $1750 \text{ N III}/1663 \text{ O III}$. $C/N = 0.1$ and $N/O = 0.9$ are found and $H/\text{He} < 0.1$ is estimated. The abundance ratio nitrogen to helium, which is derived by the ratio $1240/1640$ is very uncertain. This ratio, in fact, is affected strongly by the value assumed for the electron temperature. The abundance ratio $\text{CNO}/(H+\text{He})$ varies from 4 for $T_e = 10^4$ to 2×10^{-3} for $T_e = 2.5 \times 10^4$. The temperature independent ratios He/H and N/CNO are higher than the solar value, indicating that the material in the ejecta has experienced substantial CNO burning. Not only the ultraviolet and visual spectra of U Sco in outburst are characterized by the great strength of the He II lines. Also the spectrum of U Sco at quiescence, obtained by Williams in March 1980 (see Figure 9-7), is characterized by the strength of the He II emission relative to the Balmer lines. In this respect, the quiescent spectrum of U Sco is very different from the spectra of other quiescent novae. The classical novae present some helium enhancement, but not as much as that observed for U Sco ($Y = 0.9$ and $X = 0.1$). The high abundance of helium poses several prob-

lems that have been discussed by Webbink et al. (1987).

II.C. MASS LOSS

The mass of the shell can be estimated if the gas density, the distance, and the filling factor* are known. However, Williams et al (1981) show that when the optically thick resonance lines present in the ultraviolet can be observed, the mass of the shell can be derived by the knowledge of the optical thickness of the shell, and it is not necessary to know the distance and the filling factor.

Optical observations of the Balmer emissions provide the mass of the shell by the relation $F(H\beta) \propto N_e N_i R_s^3 \approx \epsilon N_e^2 R_s^3$ which requires the knowledge of the distance in order to obtain the flux at the stellar surface from the observed flux at the earth.

N_e can be derived from the spectral observations, hence the mass given by the product mass density ρ by R_s^3 can be derived.

The new method proposed by Williams et al. and making use of the ultraviolet observations is related only to the optical thickness of the shell along the line of sight and does not require to know the distance, the filling factor, and the density. Let us suppose that the shell of radius R_s is formed of n clouds of mean radius r . Then $\epsilon = nr^3/R_s^3$; $\tau_i = N_i a_o r$ is the optical depth of one internal cloud and the optical depth of the whole shell, $\tau_i = N_i a_o R_s \epsilon$, where N_i is the number density of the absorbing ions, a_o the absorption cross-section at the line center per ion, given by $a_o = \sqrt{\pi} e^2 f_i \lambda_i^2 / m_e c^2 \Delta \lambda_D$.

Now if we call the mean free path between clouds $l = r/\epsilon$, it follows that $\tau = \tau_i (R_s/l) = N_i a_o r (R_s/l)$, hence $\epsilon = n(r/R_s^3) = \tau_i / N_i a_o R_s = r/l$. $M_s = (4/3)\pi R_s^3 \rho$, and $\rho = (N_H + 4N_{He}) m_H = N_{He} m_H (N_H/N_{He} + 4)$ and finally, $M_s = (4/3) \pi R_s^3 m_H N_{He} (N_H/N_{He} + 4)\epsilon$.

*The filling factor ϵ is defined as the ratio nr^3/R_s^3 where n is the number of clouds of mean radius r and R_s is the radius of the shell.

Since the observations suggest that $N_{He}/N_H \approx 2$, we have $M_s = (4/3)\pi R_s^3 m_H N_{He} \times 4.5 (\tau_i / N_i a_o R_s) = 6\pi m_H (N_{He}/N_i) (\tau_i / a_o) R_s^2$, where R_s is given by the product of the expansion radial velocity by the time elapsed from the outburst.

The optical depth on the center of the strong absorption resonance lines of C IV (observable on June 28 and 30) is assumed equal to 1, since there is some residual radiation even in the center of the line. This is the advantage of using the ultraviolet range of the spectrum, where absorption lines like those of C IV are present, but the assumption that τ_i is equal to one is also the weak point of the method. Another weak point in this procedure is the determination of the ratio N_{He}/N_i , in this case the ratio of helium atoms to the absorbing ion C^{3+} . It can be derived from the spectrum but it is strongly affected by the assumed value of the electron temperature.

With all these causes of uncertainty in mind, the mass of the shell can be computed. It is found to be of the order of $10^{-7} M_\odot$. This value is much smaller than the typical values of the shells of classical novae, which have masses of the order of $10^{-4} M_\odot$.

II.D. ON THE NATURE OF THE HYPOTHETIC COMPANION OF U SCO AND AN ESTIMATE OF THE DISTANCE OF U SCO

The quiescent magnitude of U Sco estimated on a survey plate is $V = 19.3 \pm 0.5$ (Barlow et al., 1981). If we assume that this is the apparent magnitude of the cool companion, and if we assume that it is a giant (as is the case for T CrB, for a reddening $E(B-V) = 0.2$, $A_v = 0.6$ mag), then we have a distance modulus of 18.5 ± 1 mag, corresponding to a distance in the range of 30-80 kpcs, which is unacceptably high and not consistent with the moderate reddening. If we assume the companion to be a subgiant in the spectral range G5-M5, the distance estimate is 13 kpcs, which is still very large. Hence, it seems more reasonable to assume that the companion of U Sco is a main sequence star, thus obtaining an independent

confirmation of the spectral type indicated by the colors and by the comparison with some main sequence stars in the spectral range F7-K0 (Hanes, 1985). For $M_v = 4.5$, corresponding to a spectral type G0 or late F, it follows $d = 6.9$ kpcs. This distance is in good agreement with the estimate by Williams et al. (1981), by making the assumption that the luminosity of the star at outburst is equal or larger than the Eddington luminosity for one solar mass.

In conclusion, it seems reasonable to assume that the quiescent spectrum of U Sco is G0 V.

III. T PYXIDIS

Among the five accepted recurrent novae, T Pyx is that with the shortest mean period (19 years) and with the hottest spectrum at minimum. Five outbursts were observed: in 1890, 1902, 1920, 1944, and 1966. However, none of them was observed extensively, with the exception of the last one, during which members of the Variable Star Section of the Royal Astronomical Society of New Zealand (Circulars 123 ad 125) visually observed the light curve, and Catchpole (1969) obtained nine spectrograms between 12.6 and 412.5 days after the initial halt.

The light curve, as those previously observed, rises rapidly to a maximum at about 7.9 (the initial halt); then rise slowly to 7.4 during the next eight days, fall rapidly by 0.5 mag, and rise again to the principal maximum at 6.5 mag 30 days after the initial halt. Thereafter, the brightness decreases smoothly at a rate of 1 mag/34.7 days, with fluctuations of 0.5 mag around the mean, similar to those observed in several classical novae. Hence, this is the only example of a recurrent nova showing the characteristics of a slow nova.

The strict similarity from event to event is remarkable.

The spectra obtained during the first 12 and 16 days after halt are characterized by P Cyg profiles of the Balmer lines. The absorptions are sharp, while the emissions have a width of

about 300 km/s. Spectra taken 66 and 85 days after halt are dominated by strong Balmer emissions and other emissions of He I, He II, N II, O II, Fe II and [Fe II] with half-widths of about 2000 km/s (Figure 9-12). The other spectra obtained between 92 and 412 days after the halt are typical nebular spectra dominated by emissions of the Balmer lines, O III, N III and at least in the plate obtained 142 days after halt a faint feature at 5297 Å, which may be identified with 5303 [Fe XIV], first observed by Joy in 1945 (Figure 9-13). At that time (outburst of 1944), Joy (1945) observed only one spectrum 130 days after maximum when the star had faded at 11 mag. He saw several emissions of H I, He I, He II, N II, [N II], N III, [OI], [OII], O III, [OIII], [NeIII], [Ne IV], [SII], [FeV], [FeVI], [Fe VII], [Fe X], and [Fe XIV]. The expansion velocity from the half-widths of the lines was about 1700 km/s, similar to that observed in 1966. Figure 9-14 shows the variation of the profile of H Beta.

III.A. QUIESCENT STATE

The spectrum at minimum was observed by Humason (1938), 14 years after the 1920 outburst. He saw a continuum with strong 4686 He II, moderate Balmer lines and weak 5007 [OIII]. Elvey and Babcock (1943) obtained one underexposed spectrum when the star was at 15th mag. They observed only a faint continuum and no detectable emission lines. Catchpole (1969), on the contrary, observed no continuum, a strong 5007 [OIII], a very weak H Beta and a doubtful 4686 He II. It seems probable that this spectrum, taken one year and half after outburst is not a true minimum but represents an advanced nebular stage.

The colors at minimum are $B-V = 0.12$, $U-B = -0.96$ and become redder during the rise to visual maximum: $(B-V)_{\max} = +0.31$ and $(U-B)_{\max} = -0.08$ (Eggen et al., 1967), a behavior characteristic of an expanding photosphere, common to classical novae.

Ultraviolet observations give the color excess by the 2200 depression in the continuum: $E(B-V) = 0.35 \pm 0.05$ (Bruch et al., 1981).

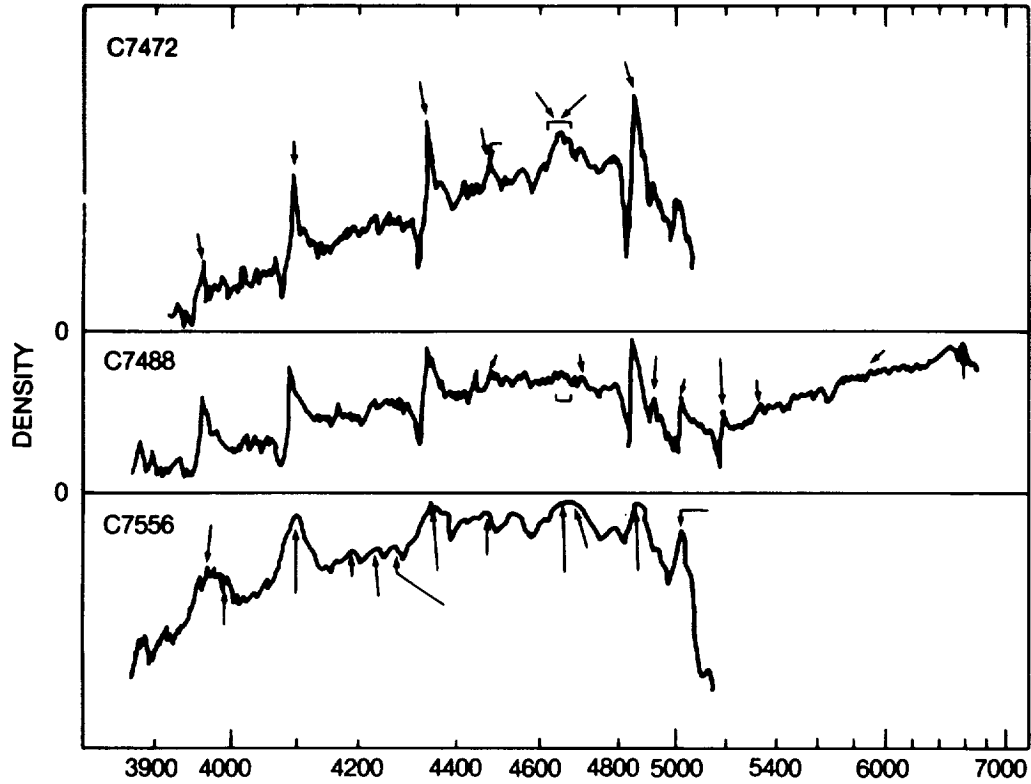


Figure 9-12. The evolution of the spectrum of T Pyx from 12.6 days after outburst (top) to 85.3 days after outburst (bottom). (from Catchpole, 1969).

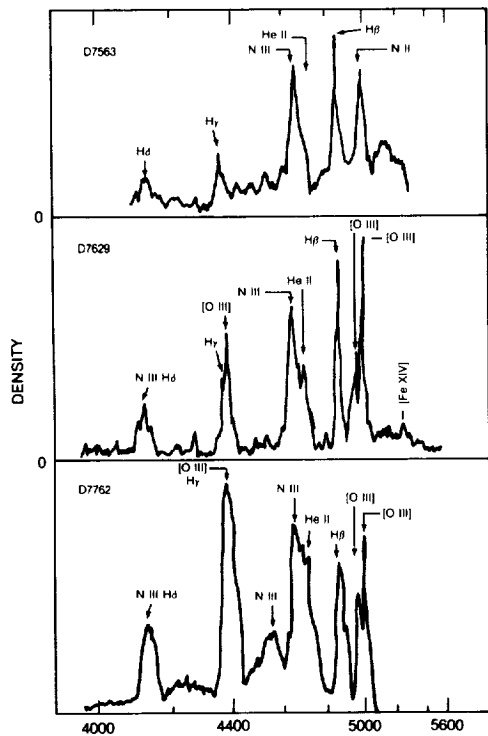


Figure 9-13. The evolution of the spectrum of T Pyx from 92.3 days (top) to 191.2 days after outburst (bottom). (from Catchpole, 1969).

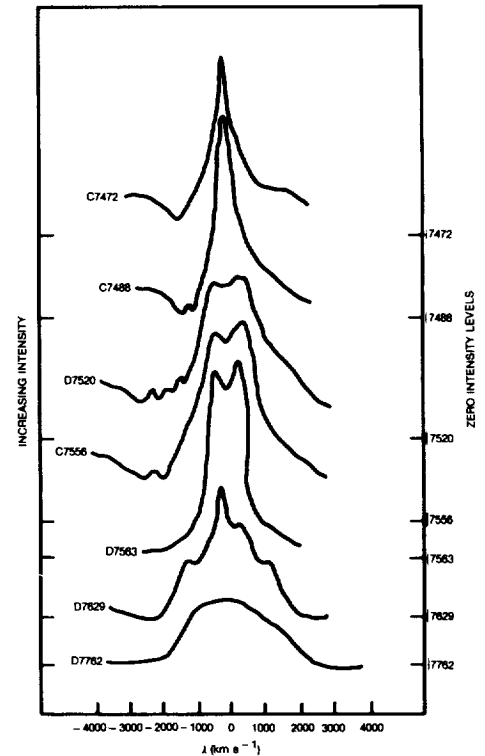


Figure 9-14. The intensity profiles of H β at various epochs. Top to bottom: 12.6, 16.5, 66.5, 85.3, 92.3, 142.3, 191.2 days from outburst. (from Catchpole, 1969).

Hence, $(B-V)_0 = -0.23$, $(U-B)_0 = -1.31$. Hence, T Pyx at minimum is extremely blue. Also, the dereddened colors at maximum, $(B-V)_0^{\max} = -0.05$ and $(U-B)_0^{\max} = -1.06$, are bluer than those of typical novae at maximum.

The low-resolution, far-ultraviolet spectrum shows a hot Rayleigh-Jeans tail. Emission lines of C II 1335, C IV 1550, He II 1640, N III 1750 are detectable. The complete absence of 2800 Mg II is remarkable. This fact, together with the extremely blue colors, are indications that no red star is present in the system. (Figure 9-15; see also Figure 6-44).

interstellar extinction $A_V = 3 \times E(B-V)$, gives M_V at maximum of -4.55. Using the Arp relation between the time of decline through the three magnitudes and the absolute magnitude at maximum, valid for classical novae, an absolute magnitude -6.5 is obtained. Hence, we have two possibilities: either the Arp relation can be applied to recurrent novae, and the interstellar calcium is weak in the direction of T Pyx (and in this case the absolute magnitude at minimum is about 2 mag, i.e., three magnitudes brighter than for classical novae at minimum) or it is not applicable to recurrent novae (and in this case the absolute magnitude at

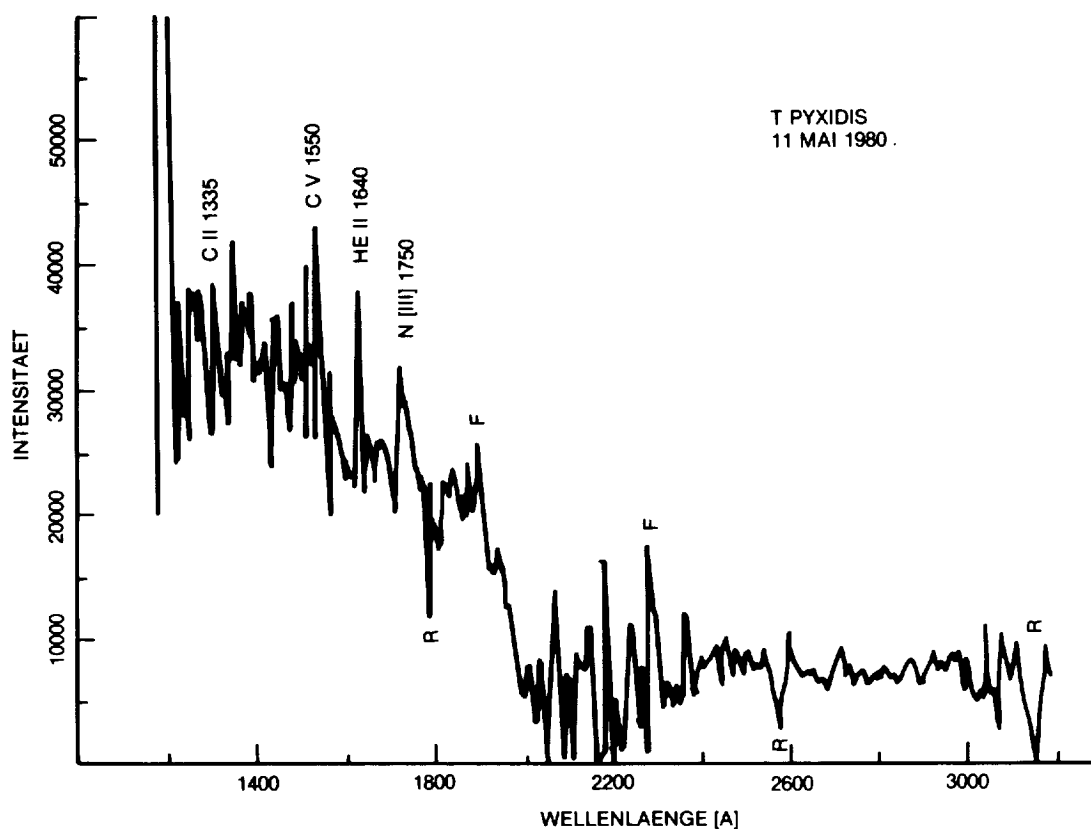


Figure 9-15. The IUE ultraviolet spectrum of T Pyx in quiescence (May 11, 1980). (from Bruch et al., 1981).

III.B. DISTANCE

The absolute magnitude of T Pyx is estimated by the intensity of the interstellar lines of Ca II. A distance of 1050 pcs is obtained, which, coupled with the apparent magnitude at maximum of 6.5 and taking into account the

minimum, approximately 4.3, is comparable to that of classical novae).

III.C. THE ENVELOPE SURROUNDING T PYXIDIS

T Pyx is surrounded by a strong remnant nebulosity. Observations of this shell have

been made in 1979.0, in 1980.2, and in 1982.9 (Seitter, 1987; Williams, 1982). Isophotes of this shell in 1979.0 and 1982.9 show remarkable differences. The relative intensities across a scan line through the center of the star in the image of 1982.9 is given by Seitter (Figure 9-16). The intensity distribution suggests that we are observing the remnants of several previous explosions. A spectral scan of the northern part of the shell is given by Williams (1982). The intensities of [OIII] 5007 and 4363, using the nebular theory (Osterbrock, 1974) gives an electron temperature of 29000 K. The ratio H/He can be derived by the ratios 5876 He I/H Alpha and 4686 He II/ H Beta, which give the He⁺ and He⁺⁺ abundances relative to hydrogen in the hypothesis that all of the lines are formed by recombination. The result is (He⁺ + He⁺⁺)/H = 0.04 + 0.02 = 0.06, i.e., a helium abundance, which, within the uncertainties of the assumptions, indicates a slight deficiency of helium

(in contrast to the determinations for other recurrent novae, which show an excess of helium). Although an exact determination of the abundances of CNO is not possible, there is no evidence of an enhancement of these elements, an enhancement that is a general property of classical novae, but which has not been found in the recurrent nova U Sco.

Seitter (1987) comparing the images of the envelope obtained in 1979.0 and in 1982.9, observes that the two images can be superposed after a rotation of about 20 degrees (Figure 9-17 by Seitter). She observes that a real rotation would imply velocities of 6000 km/s at large distance from the star, which must have transferred the angular momentum to the shell; hence, the central velocities are too large. She suggests that the rotation is apparent and the changes in intensity are not associated with real nebular motions,

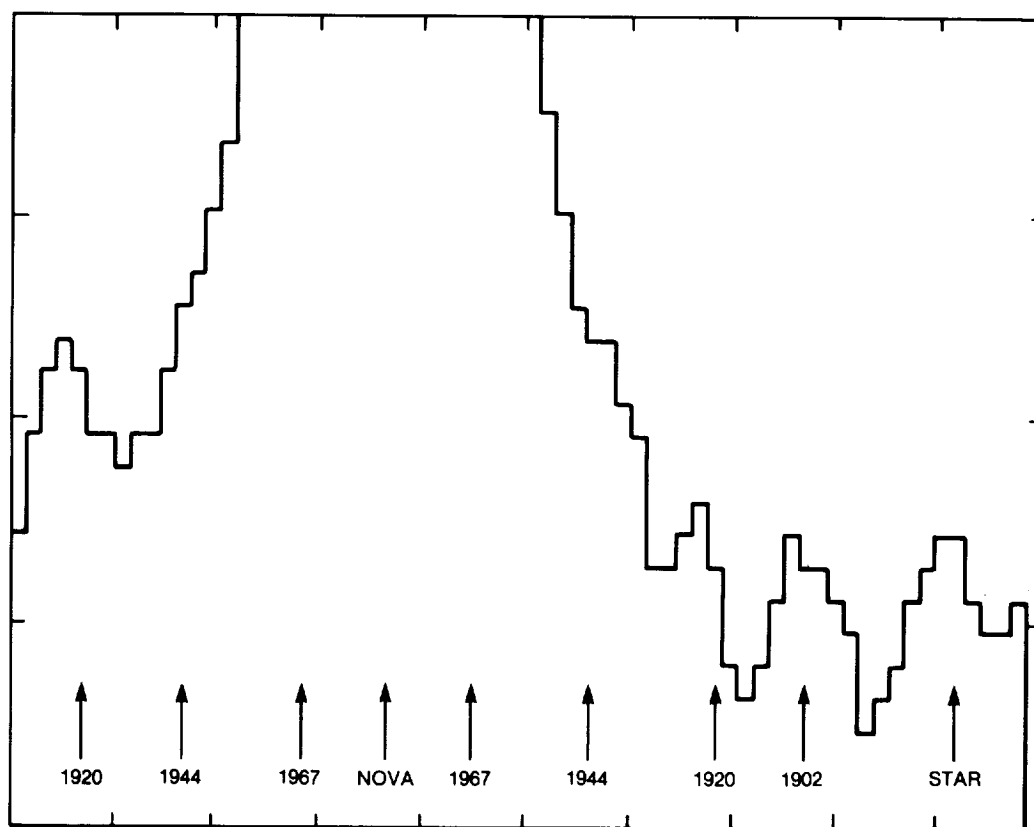


Figure 9-16. Scan line showing shell features of various outburst of T Pyx. (from Seitter, 1987).

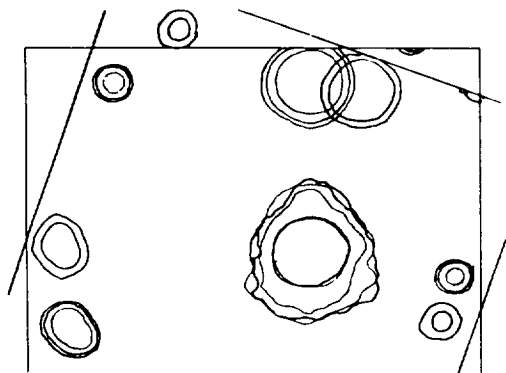


Figure 9-17. Superimposed images of T Pyx from 1979.0 and 1982.9. The earlier image was rotated relative to the later one until the inner isophotes of T Pyx matched best. (from Seitter, 1987).

but are due to changing illumination from the central star. These changes can be explained by assuming an illuminating source situated at one of the poles, changing orientation relative to the nebula because of precession. Since the directional changes amount to 20 degrees in 4 years, the precession period is of about 72 years, which suggests the presence of an unseen companion orbiting with a period of about 100 days, according to the relation between orbital and precession periods (Kopal 1985, private communication; see Seitter, 1987).

IV. RS OPHIUCHI

Outbursts were recorded in 1898, 1933, 1958, 1967, and 1985. RS Oph in quiescence is an 11th magnitude star. It is very similar to T CrB. It shows very high ejection velocities at maximum; it is a very fast nova (but not so fast as T CrB); it develops high-excitation forbidden emission lines during late decline. The main difference is that the outburst light curve of RS Oph does not present a secondary maximum, as is the case for T CrB (*).

(*) A full conference has been devoted to RS Oph on Dec. 1985. The proceedings have been published by the VNU Science Press: "RS Ophiuchi (1985) and the recurrent nova phenomenon," ed. M.F. Bode, 1987.

IV.A. THE OUTBURST EPISODES

The outburst of 1958 was the most extensively observed in the past, while that of 1985 was observed almost simultaneously in the X-rays, ultraviolet, optical, infrared, and radio waves at many epochs.

IV A.1. THE OUTBURST OF 1898

Emission lines of H, He I, He II, and N III were observed by Pickering (1905) in two spectra obtained in 1898, July 14 and 15. The star was of 7.7 mag on June 30 and declined steeply in July and August. Extrapolating the light curve, by assuming that it was similar to those observed in the successive outbursts, the maximum must have occurred around June 19, with mag 4 or 5.

IV.A.2 THE OUTBURST OF 1933

On August 12, 1933, RS Oph was observed by an amateur astronomer, E. Loreta (see Rosino, 1987), to have reached the visual magnitude of 4.3. The spectral evolution was described by Adams and Joy (1933) and by Joy and Swings (1945).

Emission lines of H, He, Fe II, Ca II, and Na I were observed from August 16 to September 11, with a faint P Cyg absorption component. The strongest emissions were about 25 Å wide, corresponding to about 1500 km/s. Comparatively sharp nebular lines appeared in the following order: 4362 [O III] on August 18, 5006 [O III], 4640 N III, and 4686 He II on August 29, 3868 [Ne III], 3967 [Ne III], and 4959 [O III] on August 30, [Fe II] on September 11, and 4068 [S II] on October 1. The coronal lines were definitely identified on October 2. At the end of October, 5303 [Fe XIV] was comparable in intensity to H Beta, and 6374 [Fe X] was twice as strong as 5875 He I. In March 1934, the coronal lines had disappeared.

IV.A.3 THE OUTBURST OF 1958

The maximum occurred on July 14.5. The development of the outburst of 1958 has been observed since the first night, and it was very similar to the previous one of 1933. During the first six days, the decrement was of 0.35 mag/day (Tolbert et al., 1967). The very red color of the star during the first day and the comparison of the observed Balmer decrement with the theoretical one (although classical models can only be applied with difficulty to nova envelopes) suggest that the star is strongly reddened (see Walker, 1977; Dufay and Bloch, 1964). Recent ultraviolet observations made with IUE actually indicate $E(B-V) = 0.73$ from the 2200 feature. However, the galactic position of RS Oph makes it difficult to justify this strong reddening (Svolopulos, 1966). It is possible that it has circumstellar origin. However, this reddening is similar to that of the Cepheid Y Oph, which lies close to the same line of sight, and this fact suggests that the reddening is mainly interstellar (see Evans, 1987).

One year after outburst, the continuum was cut by several absorption lines typical of a late-type star, and the color temperature (without correction for reddening) was of the order of 3900 K (Dufay and Bloch, 1964). Since the absolute photographic magnitude of the nova at maximum was about -8.7 (from the Arp relation between rate of decline and magnitude at maximum, assuming it applicable to recurrent novae) and it brightened by about 7 magnitudes, the absolute magnitude at minimum is about -1.7, thus suggesting that the late-type star is a giant, as in the case of T CrB. However, as we shall see in the following (see Section IV.C.4), the distances inferred from the interstellar extinction and from the interstellar line absorptions do not agree with the value derived from the Arp relation and indicate a value of M_v max less bright than -5. It follows that the absolute visual magnitude at minimum is included between -1.7 and +2.

A detailed description of the spectrum and its variation from the outburst to about one year later is given by Wallerstein (1958) and by

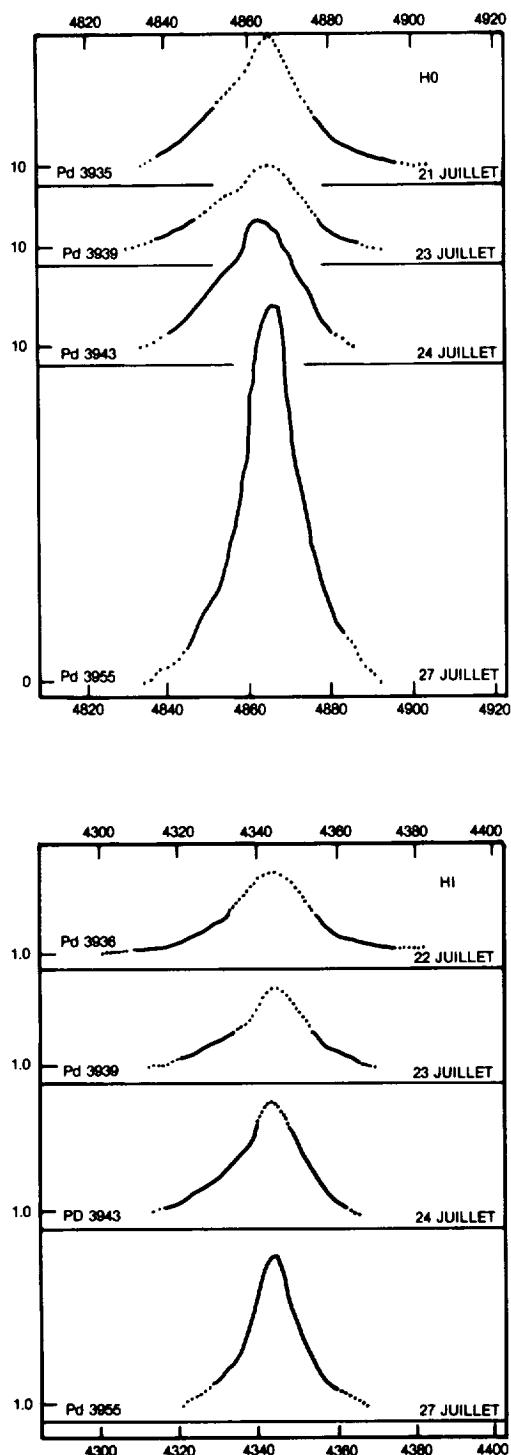
Dufay et al. (1964). Just before maximum, the spectrum appeared very flat and almost featureless, with the exception of the Balmer line emissions, which, however, were very broad and flat. The profiles of the Balmer emissions, in contrast to those of classical novae, had a much simpler structure as shown by Figure 9-18.

The night of July 14, 1958, the star was of 5th mag, while the day before, Peltier reported that the magnitude was 11.1 (see Sky and Telescope 17,555,1958). On the first night, one observed very broad hydrogen emissions (about 1000 km/s wide) and superposed on them very sharp emissions and equally sharp violet-shifted absorptions. Broad, hazy absorption features are also present, violet-shifted by -3000 to -3600 km/s (and by about -1000 km/s on the following days).

The nonmetastable lines 4471 He I and 4481 Mg II were present in absorption on the first day only; the sharp H Alpha emission and absorption disappeared on the 8th day. The sharp absorption due to He I 3888 remained present until the 14th day after the outburst. All the sharp absorption lines showed no change in velocity during the nights following the outburst. Hence, they cannot be formed in the violently expanding nova shell, but in a slowly expanding envelope (the radial velocity of these lines is about -60 km/s) surrounding the whole system, which was probably present before the explosion. The broad emissions and absorptions, on the contrary, are formed in the nova envelope. The size of the nova envelope can be evaluated from the expansional velocity at the time of the outburst, about -3000 km/s and the time of disappearance of the sharp absorption lines, when the nova shell reaches the region of the circumstellar shell, where the sharp lines are formed. It is found that the region of absorption of Mg II and He I has a size of about 1.7 A.U., that of the H I absorptions, of about 7 A.U., and that of the metastable line 3888He I, of about 22 A.U.

Emissions of Fe II, [Fe II], [Fe III] appeared on the second, fourth, and seventh night, re-

spectively, and have all the same velocities, suggesting that they are all formed in the same place in the envelope.



Numerous coronal lines appeared in August and September: [Fe X], [Fe XIV], [A X], [A XI], [Ni XII], [Ni XV]. From February to June 1959, the coronal lines disappeared completely, while the forbidden lines of O I, O III, and N II were rather strong but less than the permitted lines.

The very similar spectral evolution in 1933 and 1958 suggests that the outbursts give rise to a well-regulated mechanism able to reproduce a sequence of several complex phenomena in all their details and in the same chronological sequence.

Figures 9-19 through 9-25 show the evolution of the spectrum of RS Oph from the night of the outburst (July 14, 1958) to Oct. 19 of that year.

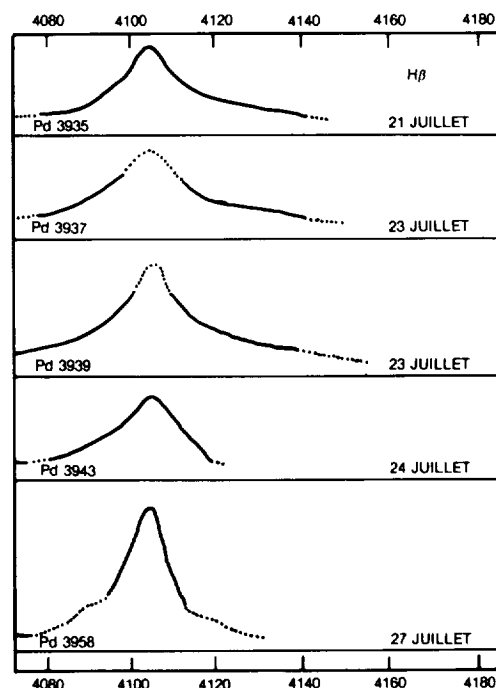


Figure 9-18. The profiles of H Beta (a), H Gamma (b), and H Delta (c) of RS Oph for the period July 21-27, 1958 during the second week following the outburst. (from Folkart et al., 1964).

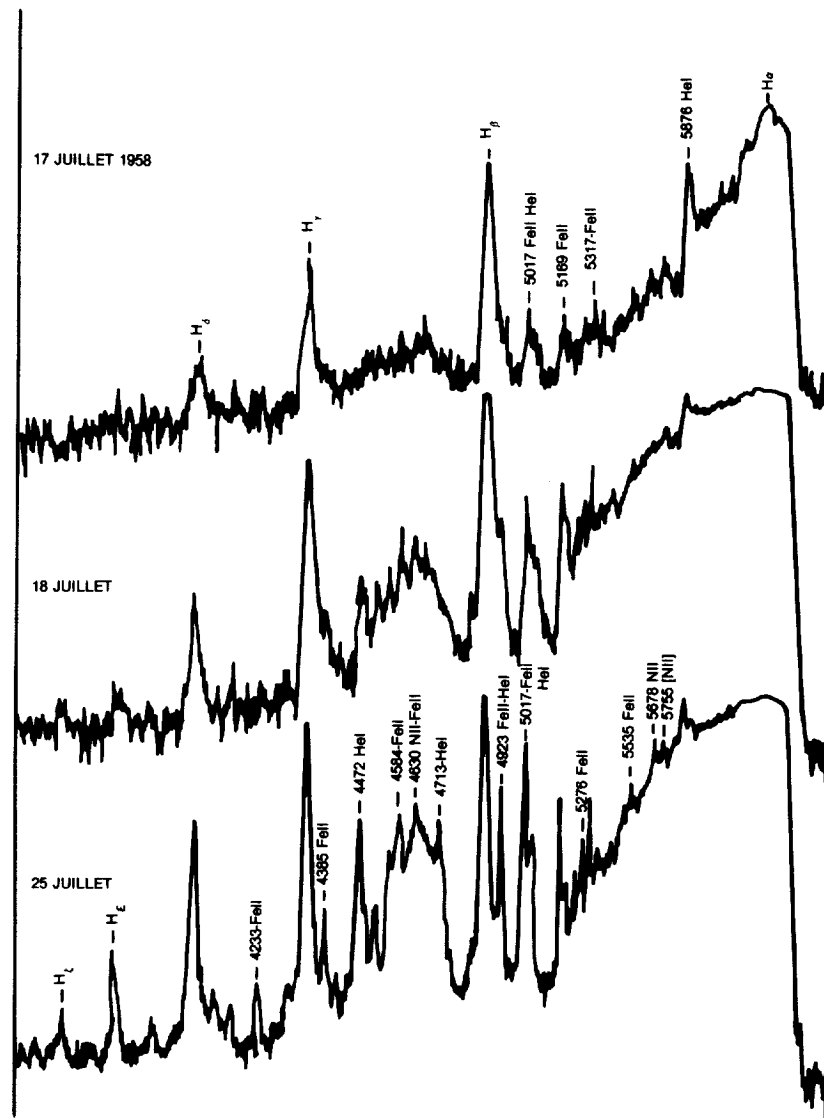


Figure 9-19. Evolution of the spectrum of RS Oph. Region H Alpha-H epsilon.
(from Dufay et al., 1964).

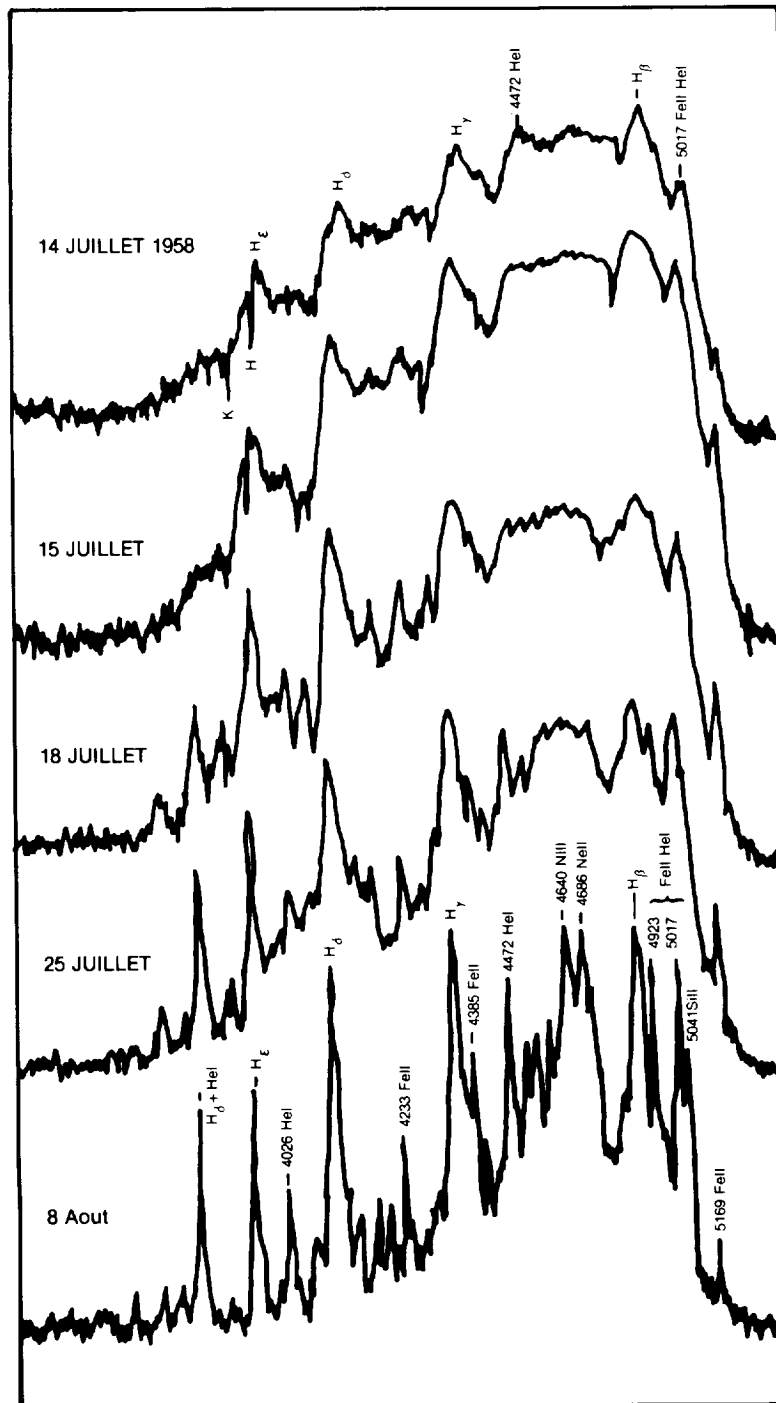


Figure 9-20. Evolution of the spectrum of RS Oph. Blue region.
(from Dufay et al., 1964).

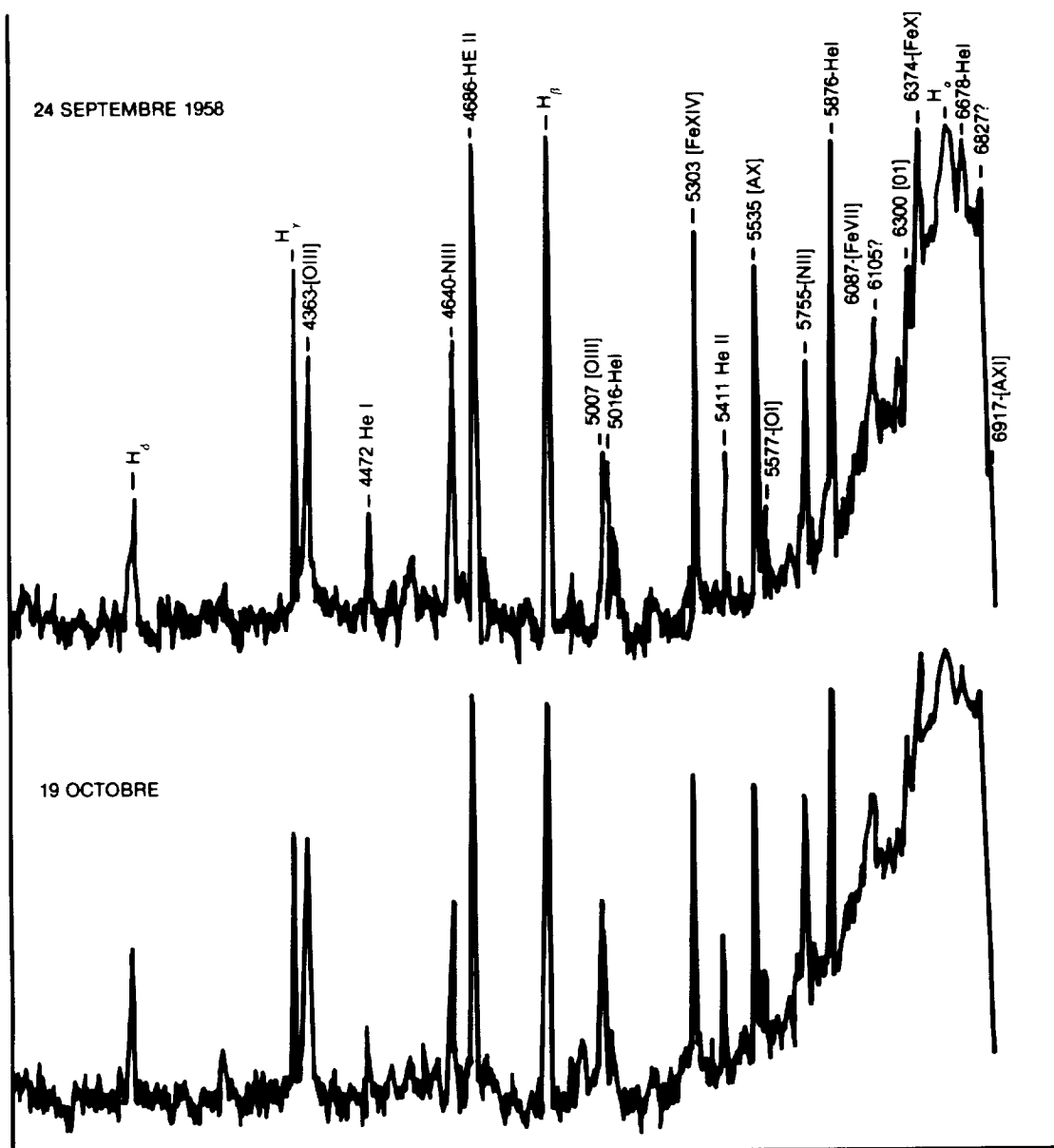


Figure 9-22. Evolution of the red region of the spectrum of RS Oph in September and October 1958. (from Dufay et al., 1964).

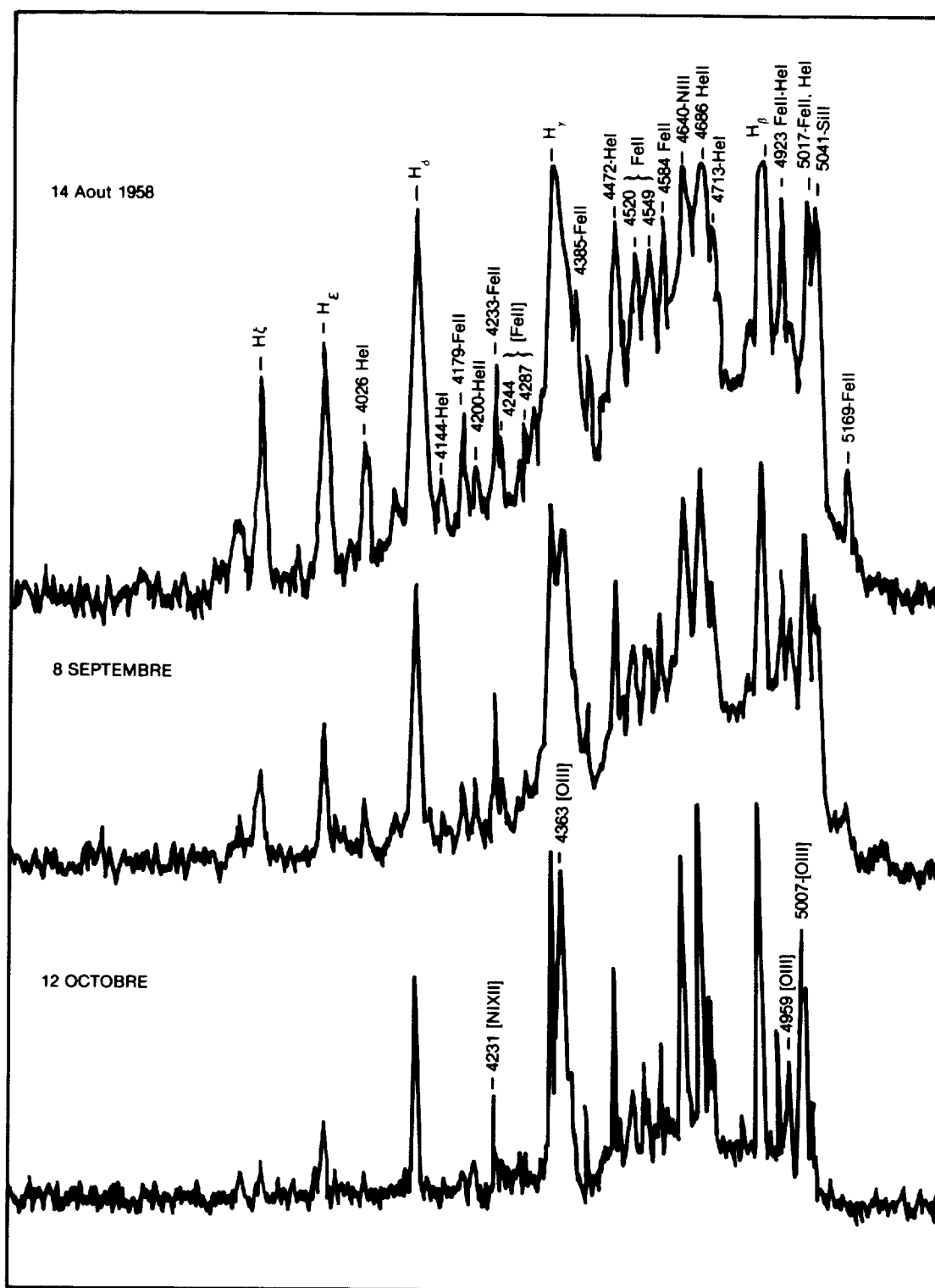


Figure 9-23. Evolution of the blue spectrum of RS Oph from Aug. 14 to Oct. 12, 1958. (from Dufay et al., 1964).

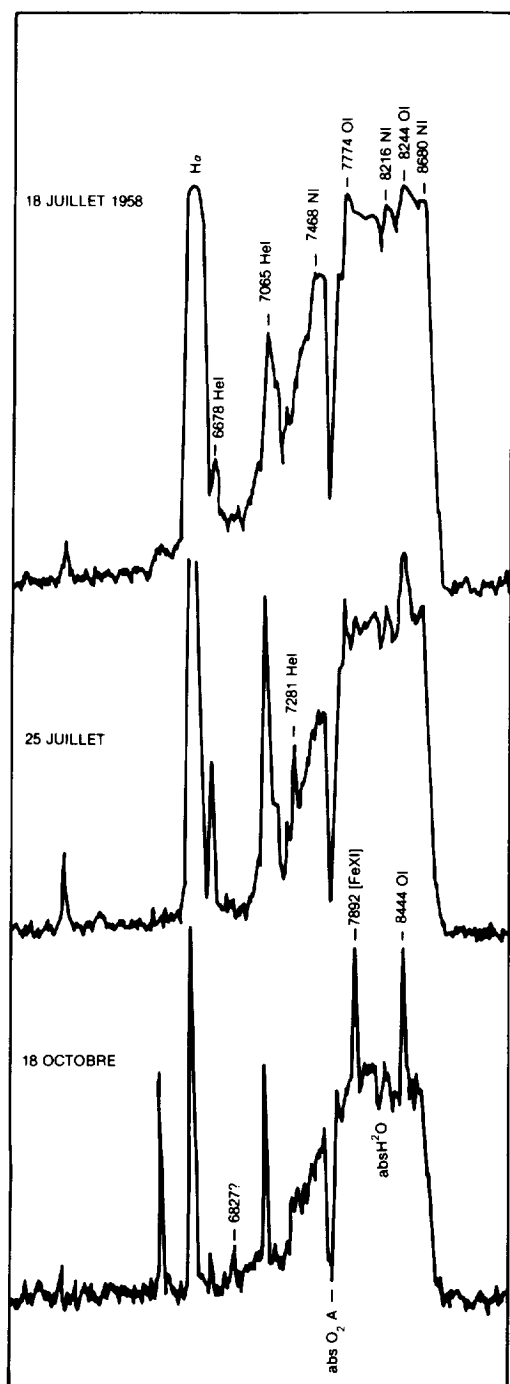


Figure 9-24. The infrared spectrum of RS Oph from July 18 to October 18, 1958.
(from Dufay et al., 1964).

IV.A.4. THE OUTBURST OF 1967

The outburst started on October 26, 1967, was observed spectroscopically in Asiago from October 27 to the beginning of November when the star was very low on the horizon (Rosino,

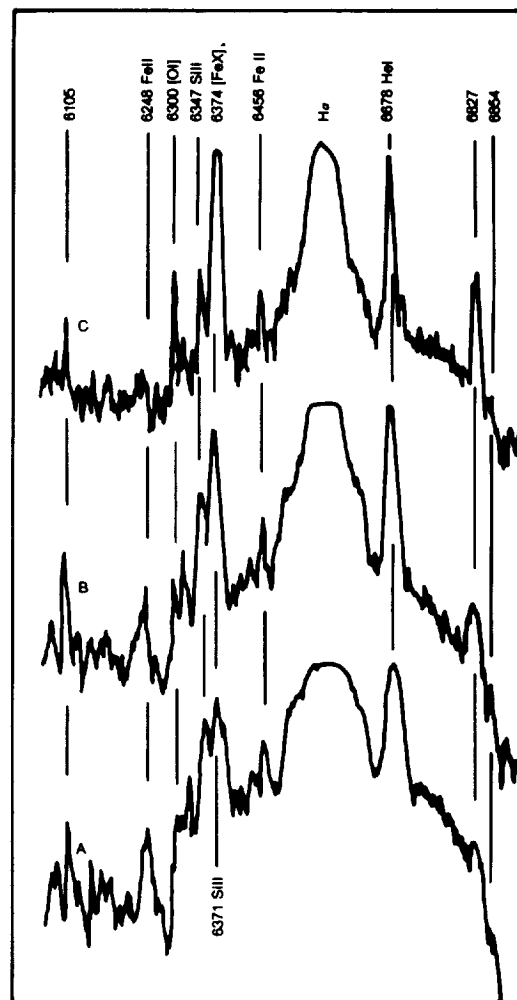


Figure 9-25. Appearance of the forbidden lines 6374 Fe X, 6827 Ca X (?), 6855 Ca X (?). A: August 10, 1958; B: August 12, 1958; C: September 4, 1958. (from Dufay et al., 1964).

1987). Broad emission bands of hydrogen and helium with two absorption systems violet-shifted by -3600 and -2700 km/s were observed on October 27. Near the center of each emission band, a sharp emission with a narrow P Cyg absorption at -40 km/s was present. Four to five days after maximum, the broad absorptions become weaker and then disappeared, while the He emissions become dominant. At the beginning of November, forbidden lines of O III, Ne III, and Fe X were present. In February 1986, when it was possible to observe the nova again, the spectrum showed strong and wide Balmer emissions, He I and He II emissions, and coronal lines of [A X], [Fe X], and [Fe XIV].

IV.B. OBSERVATIONS IN QUIESCENCE

A few spectroscopic observations were made by Wallerstein (1963) in 1960-62 in correspondence of a minor outburst to mag 10. Also, in this almost quiescent period, the spectra present emission and absorption lines characteristic of a shell; that is : Balmer lines observable in absorption up to H 30, absence of the non-metastable, high-excitation line of Mg II at 4481 Å, Fe II lines in emission, strong absorption lines of Ti II, and a few emissions of [Fe II], but no nebular lines.

From these observations, Wallerstein (1963) underlines the following points:

a) No late-type spectrum is visible in the blue region; even 4226 Ca I is not present. Hence, at this time RS Oph is similar to T CrB.

b) The spectrum in 1960-62 was practically the same as that observed by Sanford (1947b). This means that the basic physical processes occurring at minimum were not changed by the 1958 outburst. The two magnitude changes that occurred in 1960-62 were not accompanied by significant spectral changes.

c) The absorption lines H and K of Ca II are more negative by 10 km/s relative to the other shell lines, suggesting that an expanding circumstellar envelope is still present.

d) Emission lines of hydrogen and Fe II have shown an abrupt violet shift between 1960 and 1961 (H gamma and H delta from about +25 to -230, Fe II from about -30 to -90) showing a sort of activity taking place. No similar effect was shown by He I and [Fe II] lines.

IV.C. THE OUTBURST OF 1985

The last outburst of 1985 was observed from space with EXOSAT, IUE, and IRAS; also, radio and infrared observations were made from the ground beside, of course, optical observations.

IV.C.1. OPTICAL OBSERVATIONS

On January 26.47 U.T., the visual magnitude was 6.8; on January 28.45, it was 5.2 (Morrison, 1985). On March 6.22 it was 9.4 (Medway, 1985). An extended series of spectroscopic observations was made in Asiago (Rosino and Iijima, 1987). Their main conclusions of this study are the following: The 1985 outburst has the same characteristics of the previous ones; i.e., the rapid decline, the very high velocity of the ejecta (-1650 to -3500 km/s), the presence of extremely strong coronal lines, the persistence of high excitation lines for almost nine months.

The first spectra were obtained on February 10, two weeks after maximum and continued to November 1985 with dispersions of 60 to 125 Å/mm in the spectral range 3900-6600 Å and 6500 to 9000 Å.

From days 14 to 29, the spectra were characterized by a strong continuum and broad emissions of H and He, accompanied by two systems of faint P Cyg absorptions at -3500 and -1650 km/s, and narrow permitted and forbidden emissions of Fe II and O I. At day 17 a very weak coronal line, 6374 Fe X, appeared.

From days 52 to 72, when the magnitude had declined to 9.5-9.7, very strong coronal lines of Fe XIV, Fe X, Fe XI, and A X were present, beside the emissions of H, He I, and He II.

At the end of April, when the magnitude was approaching its normal minimum value, the degree of excitation began to decrease. In the second half of May, all the coronal lines, with the exception of Fe X and Fe XI, have disappeared.

In June, the nova had reached the minimum of 12 mag, but the spectra still showed evidence of the past outburst, i.e., emissions of H Alpha, H Beta, 5876 and 7065 He I, 4686 He II, and the nebular lines of O III and N II. The only coronal line still observable was 6374 Fe X.

In October-November, only the Balmer

lines and the [OIII] doublet at 5007 and 4959 are present; the 4686 He II was not more detectable. Wallerstein and Garnavich (1986) have also made spectroscopic observations of RS Oph from days 65 to 73 after outburst and have measured the radial velocity of several low and moderate excitation lines, like H I, He I, He II, [NII], [OIII], Si II, Ti II, Fe II. Radial velocities of about -20 to -30 km/s were found while He I and He II show two components at about -20, -30, and at -170, -200 km/s. Several forbidden lines of Fe IV, Fe VI, and Fe VII, and the coronal lines of Fe XI, Fe XIV, Ni XIII, Ni XV, and Ni XVI have radial velocities included between -10 and -70 km/s, while A X, A XI, and Fe X have two components at about -20, -40, and another at about -200 km/s. These authors give a full identification list, the measured fluxes and the fluxes corrected for the interstellar reddening of all the emission lines between 3312 Å and 6918 Å.

IV.C.2. INFRARED OBSERVATIONS

The near infrared colors of RS Oph between outbursts place it close to the region of Mira

variables in the two-color diagram (J-H)-(H-K), while it lies close to the normal giant-supergiant sequence in the two-color diagram (J-K)-(K-L) (Figure 9-26a,b) (Evans, 1987). According to Feast and Glass (1974), this discrepancy could be resolved assuming a reddening $E(B-V) = 1.8$, which is in contrast with that deduced by pre and postoutburst ultraviolet observations that give $E(B-V) = 0.73$. Hence, the colors of RS Oph are not completely normal, probably because the M0 III secondary color may be modified by the presence of an accretion disk or by circumstellar material, result of previous outburst. RS Oph was detected at 12 μ m with the infrared satellite IRAS in the course of the IRAS survey in 1983 (IRAS Point Source Catalogue, 1985; Evans, 1987). Fluxes measured by IRAS photometry at 12 and 25 μ m and JHKL (*) photometry obtained by Whittet and Evans in 1981 (see Evans, 1987) are plotted in Figure 9-27 together with the planckian curve for $T = 3000$ K and with the near infrared spectrum of an M0 III star (Strecker et al., 1979). The excess at the IRAS wavelengths is evident. If this excess is attributed to the presence of dust in the RS Oph system, a dust temperature of 350 K is derived. A similar excess was observed by

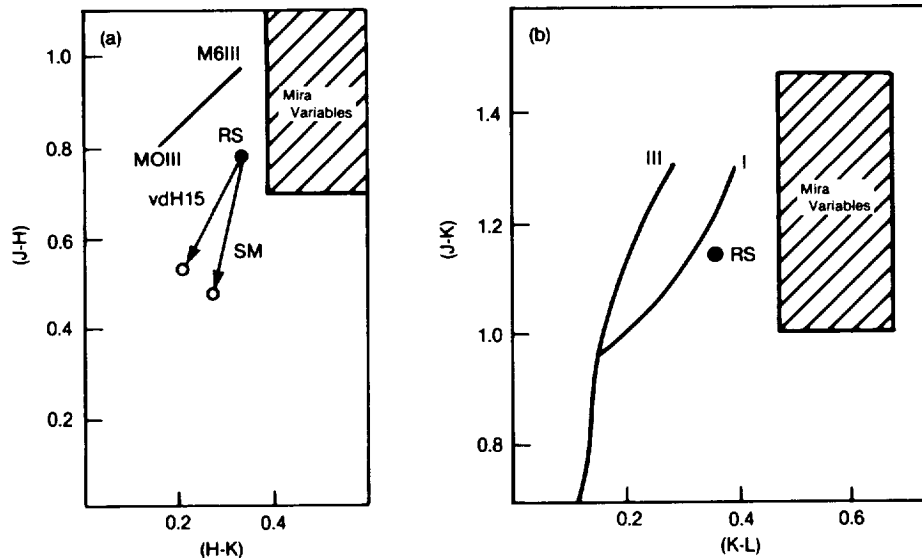


Figure 9-26. Infrared two-color diagrams for RS Oph (based on Feast and Glass, 1974). Arrows denote dereddening of $E(B-V)=0.73$. (from Evans, 1987).

J: $\lambda_0 = 1.25 \mu\text{m}$; H: $\lambda_0 = 1.62 \mu\text{m}$; K: $\lambda_0 = 2.2 \mu\text{m}$,
L: $\lambda_0 = 3.5 \mu\text{m}$

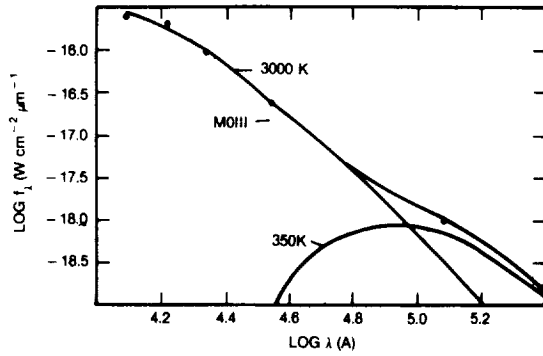


Figure 9-27. Pre-outburst photometry at JHK and from IRAS survey for RS Oph; a good fitting is obtained with an M0 III + 350 K black body energy distribution. (from Evans, 1987).

Geisel et al. (1970) for RS Oph in quiescence. This is another point of difference with T CrB, which, on the contrary, presents a negligible infrared excess.

Infrared photometry during outburst by D. Lancy (1985) indicates a strong flux in the J band, possibly due to the He I line at 10830 Å, and dust excess at longer wavelengths. Evans (1987) reports the results of infrared observations made during the 1985 outburst. The position of RS Oph in the two-color diagram (J-H)-(H-K) after dereddening indicates that the He I line at 10830 Å is dominant (Figure 9-28), at

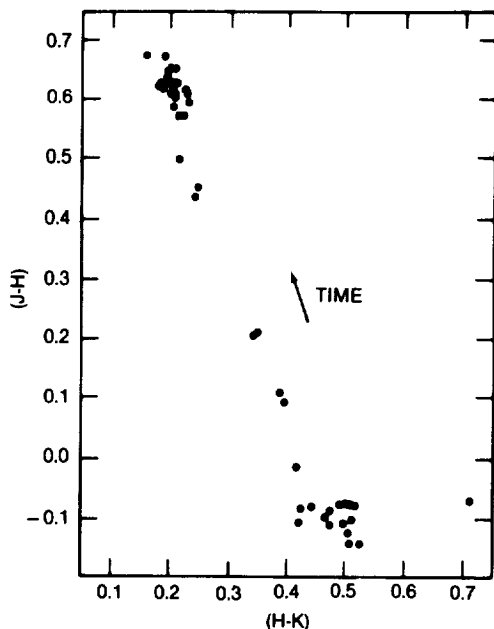


Figure 9-28. (J-K)-(H-K) diagram for RS Oph during the 1985 outburst. (from Evans, 1987).

least during the first days. The variation of (J-H) with time (Figure 9-29) indicates that the He I line starts decreasing about 35 days from outburst. The two-color diagram of Figure 9-30 shows that the position of RS Oph is consistent with the presence of two components, one at 4000-5000 K and another at 1500 K. If we assume that the component at 1500 K is due to circumstellar dust, the shock associated with the outburst could be responsible for its heating.

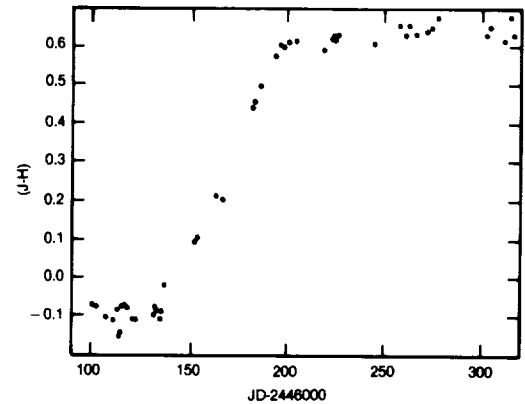


Figure 9-29. Variation of (J-K) (corrected for reddening) with time during the 1985 outburst. (from Evans, 1987).

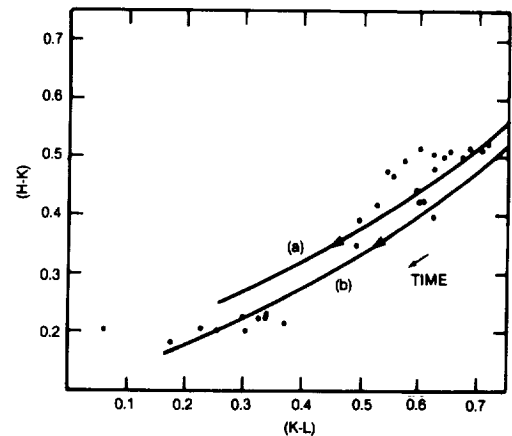


Figure 9-30. Positions of RS Oph in the (H-K)-(K-L) diagram during the 1985 outburst. The data are corrected for reddening. Curve (a) is a 4000 K + 1500 K black body combination, curve (b) a 5000 K + 1500 K combination. (from Evans, 1987).

The light curve at 1.25 μm (J) is shown in Figure 9-31.

Infrared spectroscopy during outburst has

been made by Bailey et al. (1985) with resolution $\lambda/\Delta\lambda = 100$. On the assumption that the continuum is mainly due to free-free emission, one spectrum obtained on February 21, 1985, simultaneously with ultraviolet observations with IUE (Snijders, 1987a) indicates that an electron temperature of 1.1×10^5 K fits ultraviolet and near infrared observations while an excess relative to free-free emission is evident at longer wavelengths, i.e., longer than $1.6 \mu\text{m}$. (Figure 9-32). This excess can be explained with a blackbody at 600 K, only at wavelengths shorter than $3 \mu\text{m}$; at $3.4 \mu\text{m}$, it is lower than predicted by a factor of 4. Hence, blackbody emission by dust must be ruled out. The excess could be explained by the vibration-rotation transition of CO at $2.3 \mu\text{m}$ possibly excited by the shockwave from the expanding envelope in the circumnova H II region.

High-resolution spectra ($\lambda/\Delta\lambda = 1000$ ob-

tained on June 24, 1985, are compared with the low-resolution spectra taken in February and April (Figure 9-33). In the April spectrum, we observe the hydrogen emission lines and a very strong 10830 He I line.

The highest excitation lines observed in the high-resolution June spectrum are [Si VI] $1.961 \mu\text{m}$ and [Si VII] $2.461 \mu\text{m}$. It is not surprising that no coronal lines are observable, because the maximum intensity of coronal lines in the optical range was reached in April and then declined significantly (Rosino and Iijima, 1987). However, the apparent absence of coronal lines in earlier infrared spectra is surprising. Unfortunately, no high-dispersion spectra were available.

A noticeable characteristic observed in the high-resolution spectrograms is the CO band in the spectrum of the M0 giant (see Figure 9-33).

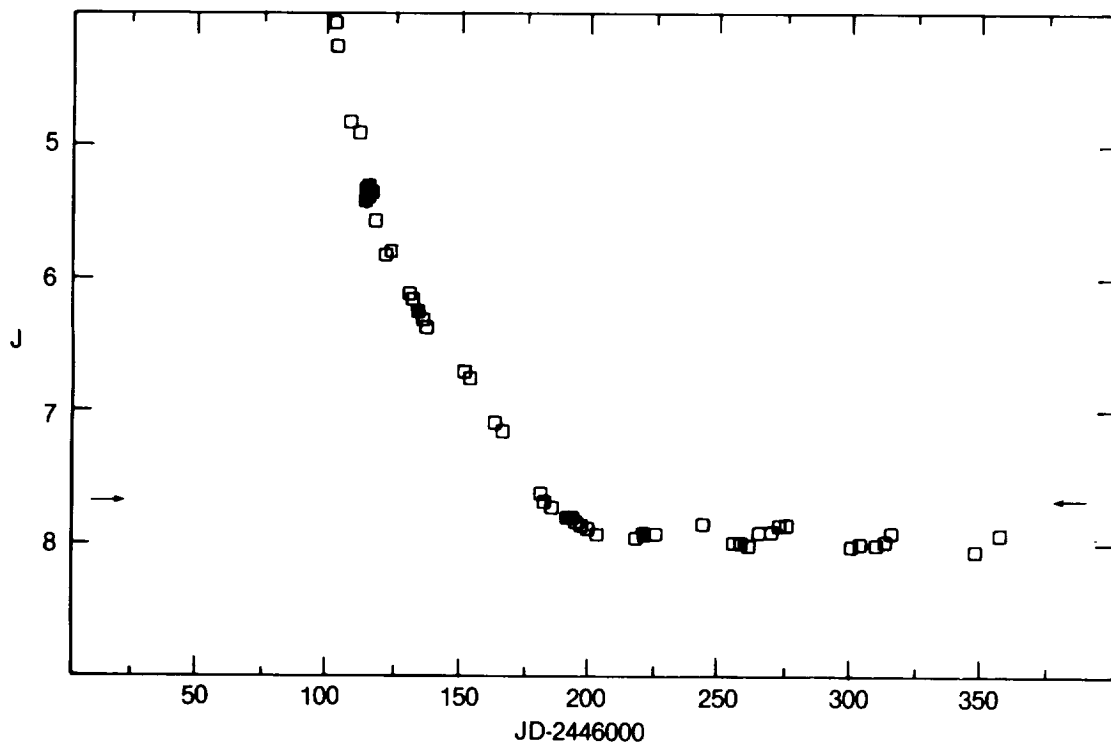


Figure 9-31. $J(1.25 \mu\text{m})$ light curve of RS Oph for 1985 outburst. The arrows show the pre-outburst J magnitude. (from Evans, 1987).

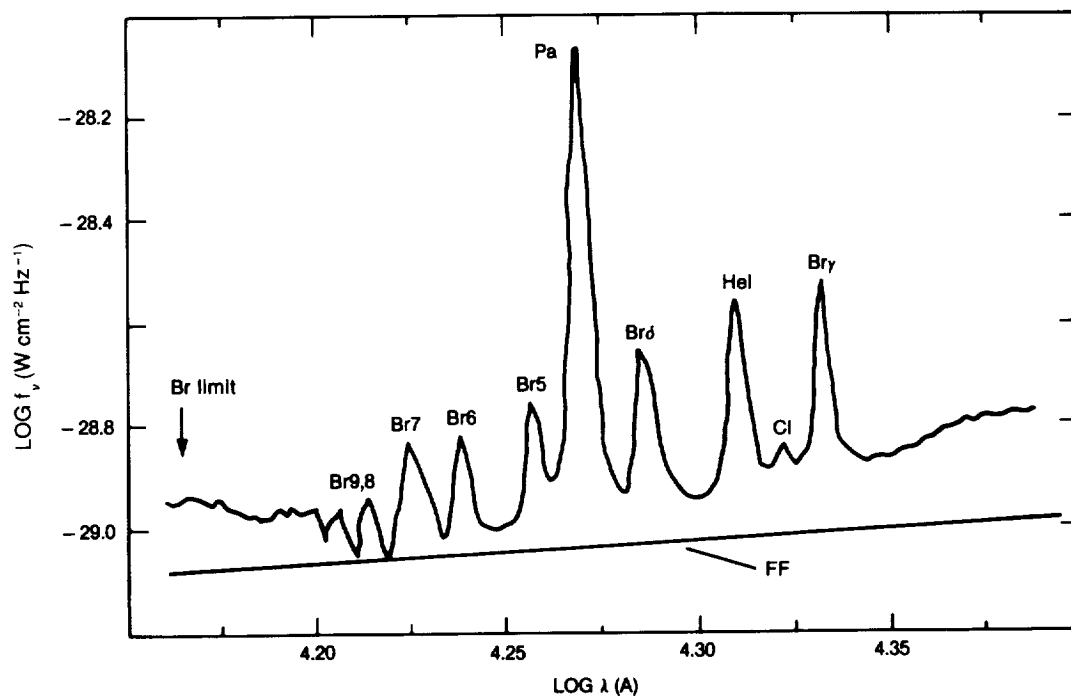


Figure 9-32. Infrared spectrum ($1.5\text{--}2.4 \mu\text{m}$) of RS Oph obtained on February 21, 1985. The line labelled FF is the nebular continuum.
(from Evans, 1987).

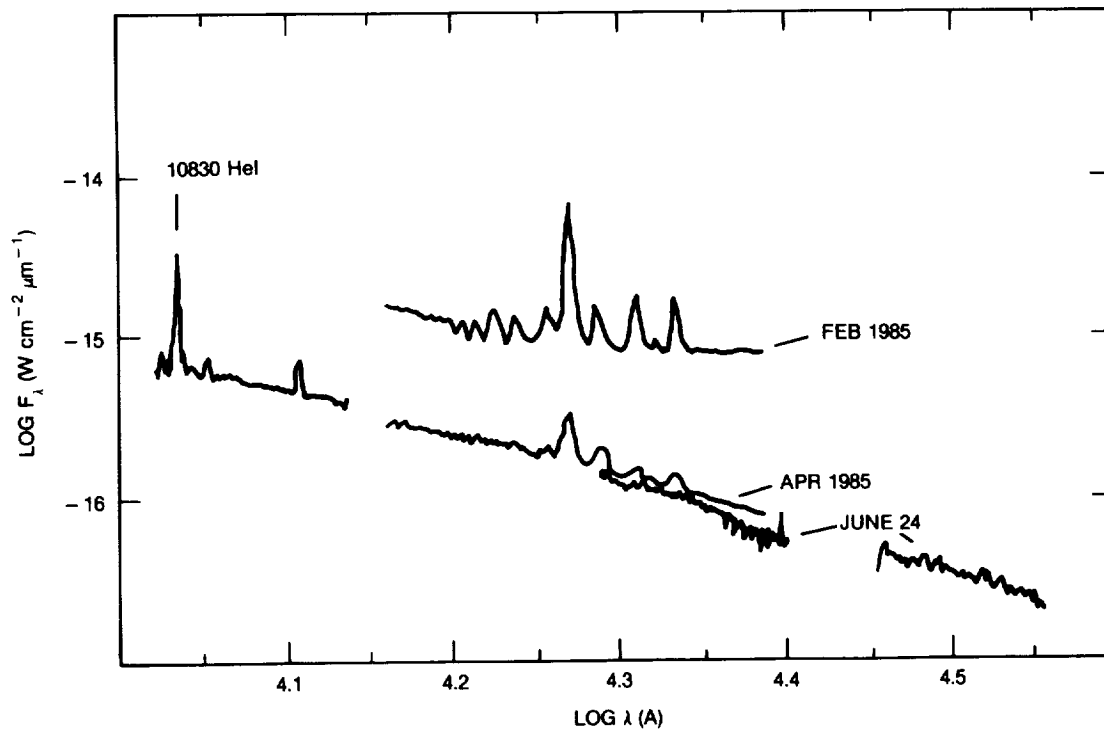


Figure 9-33. Low resolution ($\lambda/\Delta\lambda=100$) spectra of RS Oph obtained on February and April 1985 and the high resolution spectrum ($\lambda/\Delta\lambda=1000$) obtained on June 24, where the CO bands of the M giant are clearly visible.
(from Evans, 1987).

IV. C.3. RADIO WAVE OBSERVATIONS

RS Oph has been detected also at radio waves (Padin et al., 1985), and details are described by Davis (1987). This is the first detection of radio emission from an outburst of a recurrent nova. Radio emissions from classical novae have been detected in several cases, but never earlier than 50 days from outburst. In this case, on the contrary, the emission was observed 18 days from outburst at a density flux of 23 mJy at 5 GHz. Two days later, on February 15, the density flux was 30 mJy. If the assumption is made that the radio-emitting layers are expanding at about 1000 km/s as indicated by the optical spectrum, and assuming a distance to the nova of 1.6 kpc (confirmed by an interstellar absorption measure of the HI 21 cm line), these measurements indicate a brightness temperature larger than 10^7 K. This is another important difference with classical novae. In fact, the radio envelopes of the latter have a brightness temperature of 10000 K, typical of an envelope of ionized hydrogen. The high value of the brightness temperature suggests a nonthermal origin for the radio emission.

Figure 9-34a shows the radio "light-curve" at

5 GHz. Initially there is a rapid increase in flux density at the rate of about 4 mJy per day until February 18. Then there is a slower linear increase, which, projected back to the time of the outburst t_0 , gives a $(t-t_0)$ dependence of 1.7 mJy per day, characteristic common to the observed classical novae. The maximum of about 70 mJy was reached 37 days from outburst and then the decay started and a value of 30 mJy was reached on day 77 from outburst.

Spoelstra et al. (1987) have observed RS Oph with the Westerbork Synthesis Radio telescope (WSRT) at 327 MHz and with the Cambridge 5 km radio telescope at 5 GHz. A remarkable event was observed by Spoelstra et al. at 5 GHz: a radio flare occurred 41 days after outburst, about 3 days after the maximum of radio flux. The intensity of the flare was 80 mJy, and it lasted more than 1 hour and less than 1 day (Figure 9-34b).

The spectrum on day 48 from outburst (March 15, 1985) is shown in Figure 9.35a. The data are from WSRT, Cambridge 5-km telescope, Jodrell Bank and VLA.

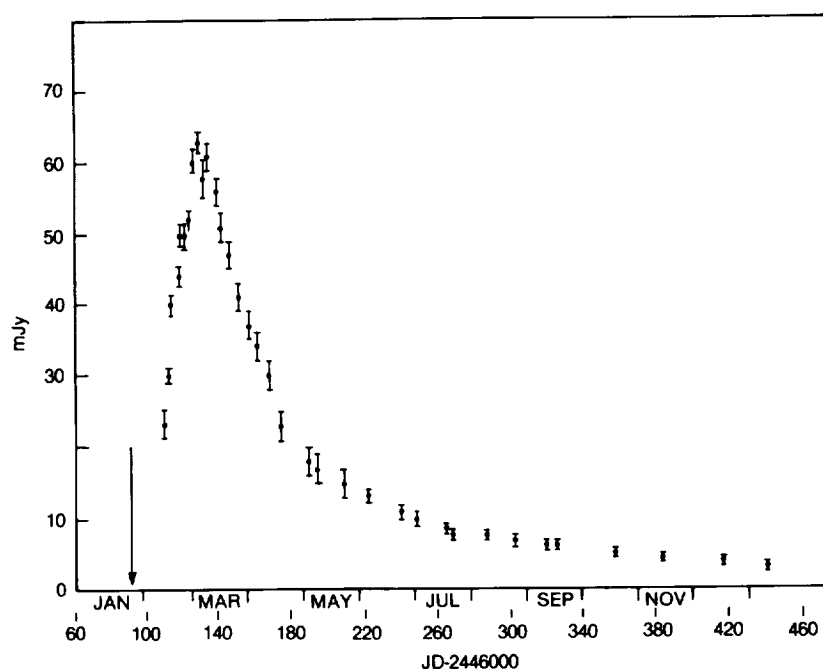


Figure 9-34. a) The 4.9 GHz "light curve" of RS Oph during the 1985 outburst (from Davis, 1987).

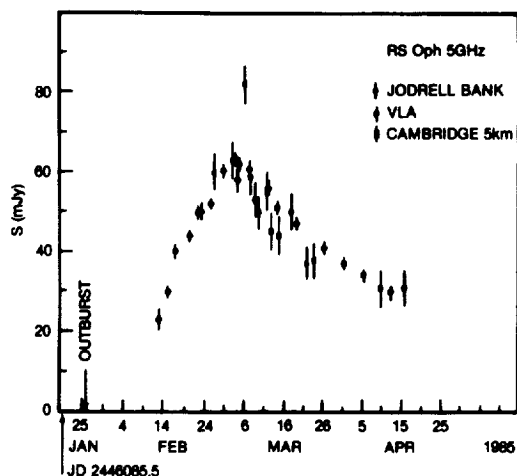


Figure 9-34. b) The 5 GHz "light curve" for RS Oph showing the "radio flare" occurred 41 days after outburst.
(from Spoelstra et al., 1987).

Davis reports the variation of the spectral behavior, which is very complex and is represented by a power law $s \approx \mu^{+\alpha}$. The variation

with time of the spectral index α is shown in Figure 9.35b for the high-frequency range (15 to 22.5 GHz) and low-frequency range (1.5 to 5 GHz). The interpretation of these variations is not straightforward.

Porcas et al. (1987) observed RS Oph using the technique of very long baseline interferometry on March 8 and on April 13. The latter observation permitted them to obtain a map of the structure of RS Oph at 1.7 GHz, when the density flux was 30 mJy. Figure 9-36 reproduces the measured visibility data, and from these data the following conclusions are drawn: a) more than 80% of the total flux of the source is present in this radio image; b) the emission is not spherically symmetric but elongated in position angle 84° ; c) the extensions along the major axis reach about 100 milliarcseconds. For an assumed distance of 2.0 kpc, this corresponds to 200 A.U. and an average expansion velocity of 4000 km/s over the 77 days from the outburst.

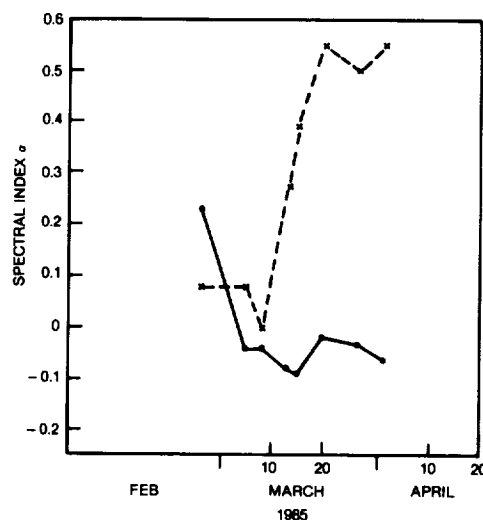
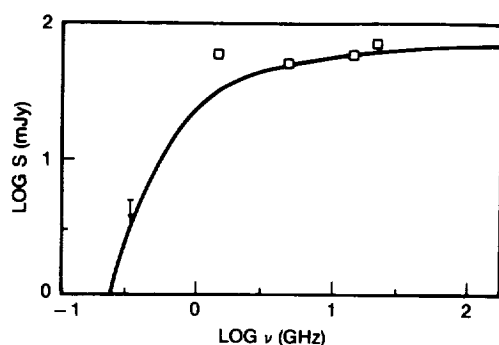


Figure 9-35. a) The radio spectrum of RS Oph on March 15, 1985. The curve is normalized to 68.5 mJy at 111 GHz. (from Spoelstra et al., 1987) b) Variation of the spectral index α for the initial phase of the outburst. dots: 1.5-5 GHz; crosses: 15-22.5 GHz (from Davis, 1987).

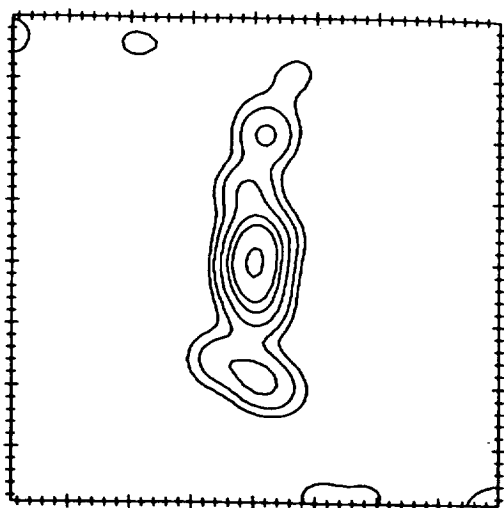


Figure 9-36. Map of the structure of RS Oph with resolution 35 milliarc sec. Contour interval: 5, 10, 20, 35, 50 and 90% of the peak brightness. (from Porcas et al., 1987)

IV.C.4. ULTRAVIOLET OBSERVATIONS

Ultraviolet observations have been made with IUE both in quiescence (Rosino et al., 1982) and in outburst (Cassatella et al., 1985). The ultraviolet quiescent spectrum indicates a state of low excitation in agreement with the indications from the optical spectrum. However, rapid changes of brightness, accompanied by the appearance of He II emission lines, are observed between two major outbursts (see, for instance, Figure 9-37 from Cassatella et al.); the 2900 Å flux was a factor of 35 higher in October 1982 than in April 1981. The recent outburst of 1985 has been monitored with IUE during the first 3 months by Cassatella et al. (1985). Spectra before outburst (of 1981 and 1982) are compared with those obtained 12 days after outburst (see Figure 9-37): the energy distribution does not change appreciably, although the flux has increased by factors between 100 and

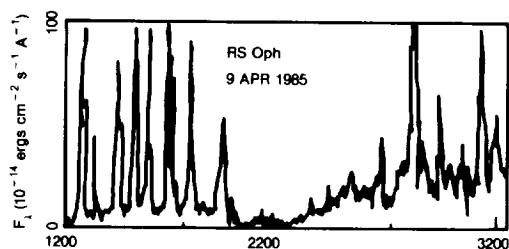


Figure 9-38. IUE low resolution spectrum of RS Oph on April 9, 1985. (from Cassatella et al., 1985)

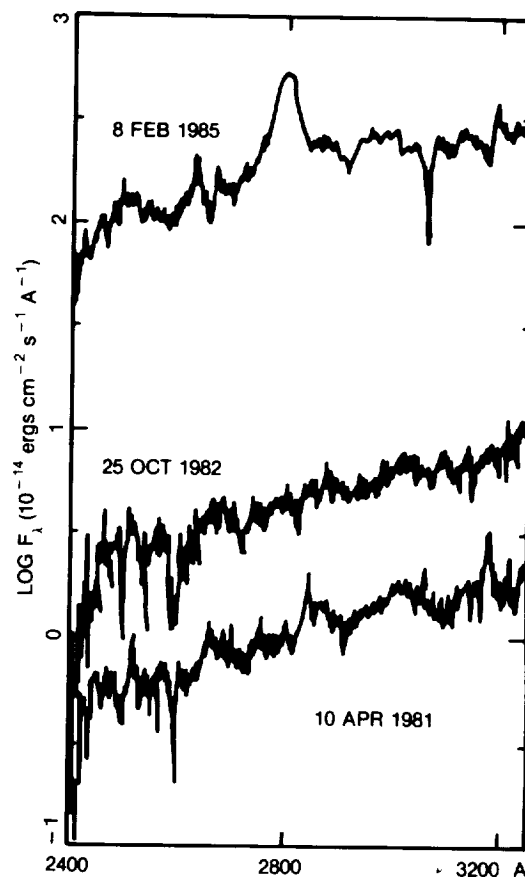


Figure 9-37. Comparison between pre-outburst and outburst ultraviolet spectra of RS Oph. (from Cassatella et al., 1985).

300. The presence of a very strong emission of Mg II is remarkable. On April 9 (Figure 9-38), about 70 days after outburst, the spectrum is dominated by strong emissions, including several coronal lines. The most prominent are Fe XI 1467 and 2649, Fe XII 1350, 2406, and 2568. It is interesting to note that the emissions from highly ionized species peak at a later stage in the decline than those for lower excitation species (see Figure 6-58). The strengthening of the high-ionization lines is accompanied by the decrease of the electron density, which is indicated by the decrease of the ratio 1893 Si III/1909 C III. This behavior is common to classical novae. High-resolution spectra, obtained with IUE, show the complex structure of the emission of C IV and 1486 N IV. It is evident that more than one component contributes to the observed profiles (Figure 9-39).

An estimate of the distance of RS Oph is made using the interstellar extinction and the

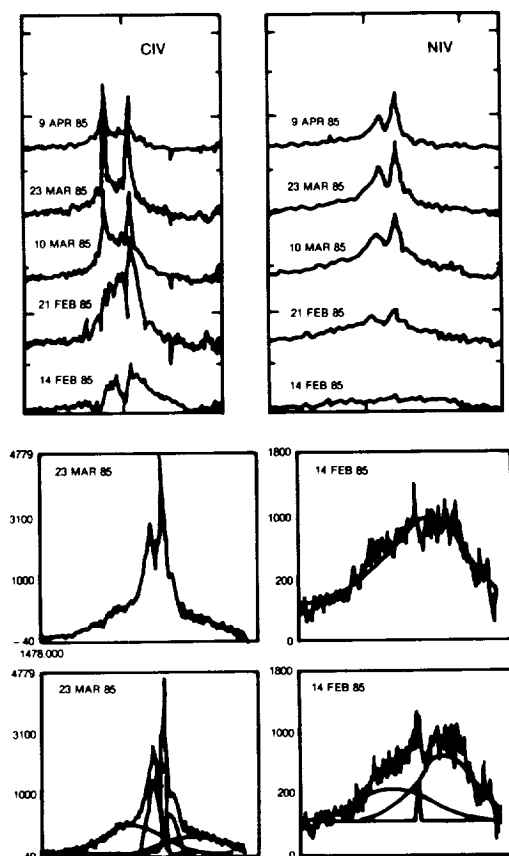


Figure 9-39. a) Variation of the CIV and NIV] line profiles, from IUE high resolution spectra. b) Attempt to represent the NIV] line at 1486 Å with three or five gaussian components at two different dates. (from Cassatella et al., 1985).

interstellar line absorption (Snijders, 1987). The interstellar extinction derived by the 2175 feature in the quiescent and outburst phase gives $E(B-V) = 0.73 \pm 0.10$. The flux ratio of the He II lines at 1640 and 3203, combined with the theoretical recombination line ratios (Seaton, 1978a), gives $E(B-V) = 0.73 \pm 0.06$, in very good agreement with the $E(B-V) = 0.76$ derived by Svolopoulos (1966). The interstellar absorption lines present in the ultraviolet spectrum are very numerous but all at velocities typical for our spiral arm and none at velocities typical for the Carina arm in the direction of the nova, at +19 km/s. This puts an upper limit of two kpc to the distance and $M_v(\text{max})$ equal or less bright than -5.

Hjellming et al. (1986) derive 1.6 kpc from the strength of the 21-cm absorption observed in an object nearby RS Oph.

The total luminosity derived by ultraviolet, optical, and infrared data (the X-ray contribution, as observed with the european satellite EXOSAT, is 0.5 to 10% of the total flux emitted on day 51, and the radio contribution is always less than 1%) is shown in (Figure 9-40) versus the time from outburst. This bolometric light curve is very similar to those of classical novae (Stickland et al., 1981; Snijders et al., 1984). On this subject, it is important to note that the decline in the ultraviolet is much slower than in the optical (see Figure 9.40).

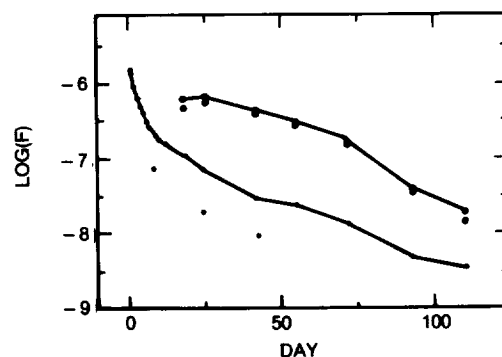


Figure 9-40. The luminosity as a function of time: small black dots infrared; curve in the middle optical; larger black dots ultraviolet, and upper curve total luminosity. (from Snijders, 1987).

An estimate of the abundances from the IUE spectra can be made using selected line ratios. Snijders (1987) derived several abundance ratios using the method employed by Williams et al. (1981). The ratio N III] 1750 / O III] 1663 is time independent from day 43 and gives $O/N = 1.10 \pm 0.17$. The C IV 1549 / N IV] 1486 can be used only on days 94 and 111 because at earlier epochs C IV has absorption components: It gives $C/N = 0.16 \pm 0.04$. The ratio N V 1240 / He II 1640 is subject to self-absorption of N V even at day 111; moreover, it is strongly dependent on the temperature. From these data it can be estimated that the ratio He/N is included between 3 and 40. There is no doubt that nitrogen is strongly overabundant, and this indicates that nuclear runaway has occurred. However preoutburst ultraviolet spectra show a very strong N III] line. This may indicate that the material transferred from the red giant is nitrogen-enriched or that we are observing the result of a previous outburst.

IV.C.5. X-RAY OBSERVATIONS

RS Oph was observed with the European satellite EXOSAT at the earliest opportunity, i.e., on March 22, 1985, 54 days after optical maximum. At earliest dates the star was too close to the sun. The observations were made with the low-energy telescope and broadband filters that gave limited spectral information in the energy range 0.04 to 2.0 keV. Additional spectral information was obtained in the medium energy range, from 1.5 to 15 keV. Six observations were made from March to October. Figure 9-41 gives the low-energy flux

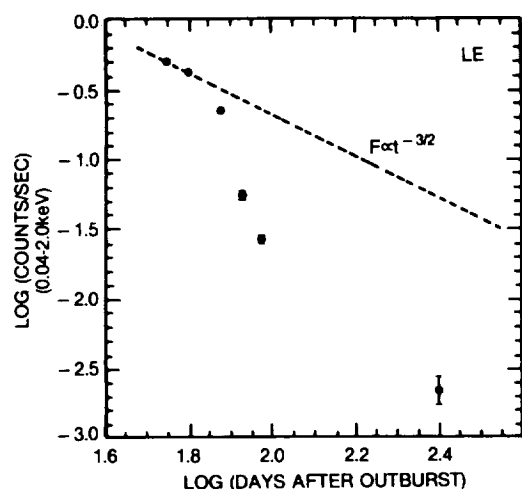


Figure 9-41. EXOSAT count rate as a function of time since the optical outburst. The dashed line is the expected decay rate of the X-ray flux according to the model of Bode and Kahn (1985).

(from Mason et al., 1987).

variation from day 54 to day 250 and, for comparison, the decay expected, according to a theory by Bode and Kahn (1985). They have calculated the expected decay of the flux due to a shock wave expanding in a medium whose density falls as r^{-2} , i.e., the expanding wind of the red giant. It is evident that the decay is much faster than their theoretical prediction. However, there are several indications that the origin of the X-ray emission is due to circumstellar gas heated by the shock wave produced by the nova outburst. In fact, the X-ray emission lasts a long time after the optical outburst, at least 250 days; there is no detectable short-time variability, indicating that the source is extended; the observed expansion velocity 50 days after outburst, as indicated by the optical emission line widths is about 500 km/s. In this

case, the temperature expected from the optical emission lines of the gas is consistent with the characteristic temperature of the X-ray spectrum; i.e., the flux in the coronal lines observed on March 18 is consistent with the flux observed in the X-ray range on March 22.

At the latest date of X-ray observations, on day 250 from outburst, IUE simultaneous observations were made. Then the ultraviolet spectrum was very faint and the only emission lines observable were N III] 1750 and a very faint Mg II 2800. It is difficult to understand why a well measurable X-ray flux was detected and no trace of it was observable in the far UV.

The X-ray spectrum is shown in Figure 9-42, and the relation of the low and medium energy measurements at the various epochs is shown in Figure 9-43.

Mason et al. (1987) observe that the strong soft X-ray flux detected from RS Oph about two months after outburst can be interpreted as thermal emission from the circumstellar gas heated by the passage of the shock wave from the nova explosion. In this respect, the environments of RS Oph are similar to those of a mini-supernova whose evolution can be studied on time scales of months instead of hundred or thousands of years. The rapid decay of the X-ray flux, in contrast with the theoretical predictions, can be explained if the shock wave has reached the edge

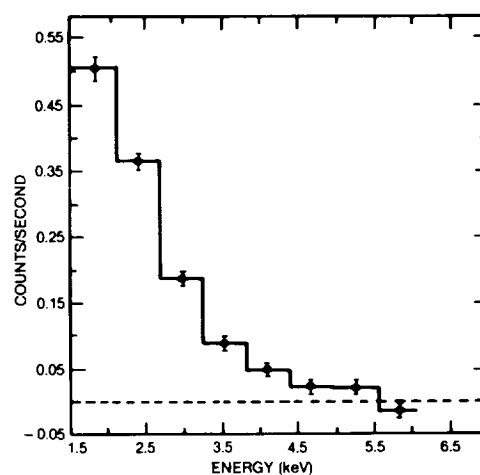


Figure 9-42. EXOSAT background-subtracted count spectrum of RS Oph on March 22, 1985. (from Mason et al., 1987).

of the cavity filled by the stellar wind of the red giant since the last nova explosion.

V. V 1017 SAGITTARII

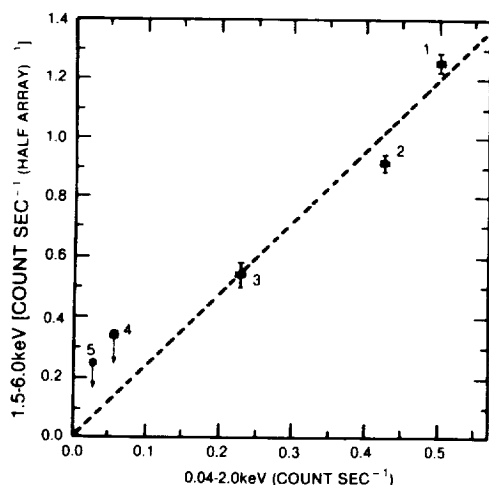


Figure 9-43. 1.5-6.0 keV count rate versus 0.04-2.0 keV count rate for the first five EXOSAT observations of RS Oph. (from Mason et al., 1987).

V 1017 Sgr is an atypical recurrent nova. It has suffered three outbursts in this century: in 1901, in 1919, and in 1973. By contrast to the other recurrent novae, these outbursts have different amplitudes. The nova is of 15th magnitude at minimum, and reached mag 11 in 1901 and 1973, while in 1919 it reached mag 7. The two minor outbursts of 1901 and 1973 have an amplitude typical of a symbiotic star rather than a nova. For this reason, it is uncertain whether V 1017 Sgr must be classified among recurrent novae or rather among symbiotics.

The light curve from 1897 to 1929 is shown in Figure 9-44, and the light curves at the epochs of the three maxima, in Figure 9-45.

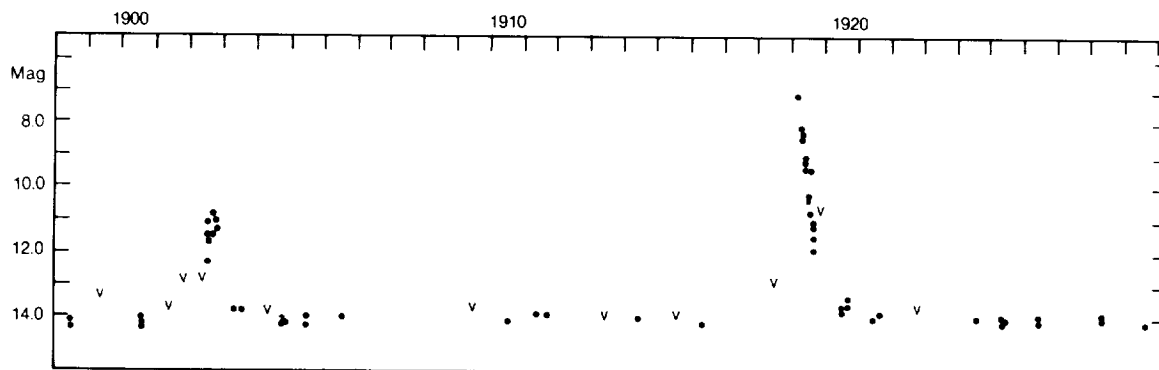


Figure 9-44. Light curve of Nova Sgr 1919. The complete curve for the interval 1897-1929. (from McLaughlin, 1946).

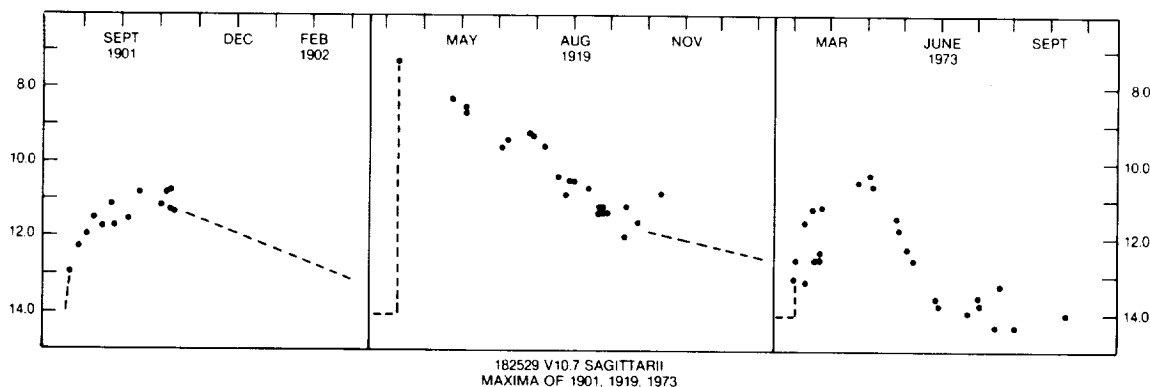


Figure 9-45. The light curves of the three observed outburst of V1017 Sgr. (from Mattei, 1974).

V.A. THE QUIESCENT SPECTRUM OF V 1017 SGR

The spectra at minimum show variations. Spectra obtained by Humason (1938) presented a strong continuum extending to the violet with no absorption or emission lines; Kraft (1964), on the contrary, reported the presence of wide Balmer emission lines in several spectra and their absence in another. The absorption spectrum suggested a spectral type G5 III.

Photoelectrical photometry at minimum has been made in the optical and infrared (for references see Webbink et al., 1987). Mumford (1971) and Walker (1977) found it to be rapidly variable in blue light by about 0.2 mag in less than one hour. The reddening, derived from the VRIJK photometry, assuming the intrinsic color of a G5 III star, is $E(B-V) = 0.39 \pm 0.03$.

V.B. THE SPECTRUM DURING THE OUTBURST OF 1973

Vidal and Rodgers (1974) observed the spectrum of V 1017 Sgr during the outburst of 1973. There are no reports of spectra obtained during the two previous outbursts.

One spectrum at premaximum, one at maximum, and one at postmaximum with dispersion of 200 Å/mm were taken during the last outburst. All three spectra are characterized by broad emission lines. The premaximum spectrum (when the star was 0.5 mag below maximum) shows a weak emission blend at 4640 and He II 4686. Some weak and broad absorption features due to Ca II H and K, a blend at 4140 (due to He I, Fe II, and Si II), the G band, He I 4388, and H beta are detectable. The spectrum taken at maximum shows no absorptions, H Alpha and H Beta emissions, and other weak emissions of [Fe II], and blends of He I+ Fe II and FeII+[Fe II]. The third spectrum taken almost at minimum does not show the forbidden lines of Fe II while the blends of Fe II+ He I at 4923 and 5017 and He I 5047 are strengthened. Similar variations, however, were observed

also during quiescent periods, as observed in the previous section.

VI. T CORONAE BOREALIS

(written by Selvelli)

VI.A. HISTORICAL OUTLINE

T CrB is a double-line spectroscopic binary, with period $P = 227.5$ days (Kraft, 1958; Paczynski, 1965), containing an M3 giant and a hotter companion whose nature has been so far rather elusive. This companion is responsible for the hydrogen and other emission lines and for the variable hot continuum, which, are superimposed over the M spectrum that dominates the optical region.

Because of these features, T CrB can also be classified as a symbiotic star. The classification as recurrent nova is based on the occurrence of two historical outbursts in 1866 and 1946, during which the star has suddenly risen from a quiescent magnitude fainter than 9.5 to magnitudes 2 and 3, respectively.

Recently, Webbink et al. (1987) have identified two subclasses of recurrent novae on the basis of their outburst mechanism:

- 1) those powered by thermonuclear runaway on a white dwarf;
- 2) those powered by the transfer of a burst of matter from a red giant to a main sequence star. One of the conclusions of the Webbink et al. study (based also on previous models and observations) has been the interpretation of the behavior of T CrB in terms of accretion onto a main-sequence star.

It is remarkable that during the two historical outbursts, the photometric and spectroscopic behaviors of T CrB were impressively similar (Pettit, 1946a), thus indicating a similarity in the physical processes responsible for the explosions. Expansion velocities of up to 5000 km/s have been reported for the H lines observed near the 1946 maximum (Sanford, 1947a; Herbig and Neubauer, 1946). In the light curve, the extremely

fast initial rise was followed (Pettit, 1946 b,c) by a rapid decline with $t_3 = 5^d$. A peculiar characteristic of the light curve was that the principal maximum ($m_v \approx 2.0$) was followed in both outbursts, and with nearly the same time separation, by a secondary maximum ($m_v \approx 8.0$). (Figure 9-46).

It is also remarkable that the two observed outbursts occurred at nearly the same orbital phase. The relevance of this fact on the model for T CrB has been pointed out by Webbink et al. (1987).

A detailed description of the outburst spectrum and its variation is given by Bloch et al. (1946), Herbig and Neubauer (1946), Sanford (1947), and by C. Payne-Gaposchkin in her book *The Galactic Novae* (1957). What is remarkable is the enormous initial expansional velocity of 4500 km/s, (or 5000 km/s if we consider the violet edge of the lines).

Sixty spectrograms were obtained at the Haute Provence Observatory by Bloch et al. (1946) during the period February 12 (three days after outburst, which occurred on February 9.25 UT) to July 15, 1946. The evolution of the spectrum is shown in Figure 9-47. We note the presence of the forbidden coronal lines 6374 Fe [X] and 5303 Fe

[XIV], which are present on February 12, reach their maximum on February 16, and disappear completely between February 20 ($\lambda 5303$) and March 18 ($\lambda 6374$). Figure 9.47 shows clearly the progressive weakening of the permitted lines and the strengthening of the forbidden ones from February 13 to April 7.

The spectroscopic observations made by Bloch et al. during the 1946 outburst permit us to draw some general remarks: the appearance of the forbidden lines and the strengthening of the high-excitation permitted lines (He II, 54 eV; N III, 47 eV;), which were observed from February 20 to April 30, are a common characteristic observed in classical novae. But a secondary maximum was observed in June; the continuum becomes stronger again and masks almost completely the TiO bands of the red giant and at the same time almost overwhelms the high-excitation lines (both forbidden and permitted). Moreover, a "shell" spectrum (blue continuum and sharp absorption lines of ionized metals) was observed in the photographic region (Sanford, 1947, Herbig and Neubauer, 1946). This phenomenon is not generally observed in classical fast novae, and classical slow novae at the moment of the secondary maximum show a nebular spectrum. The behavior of T CrB is instead rather similar to that

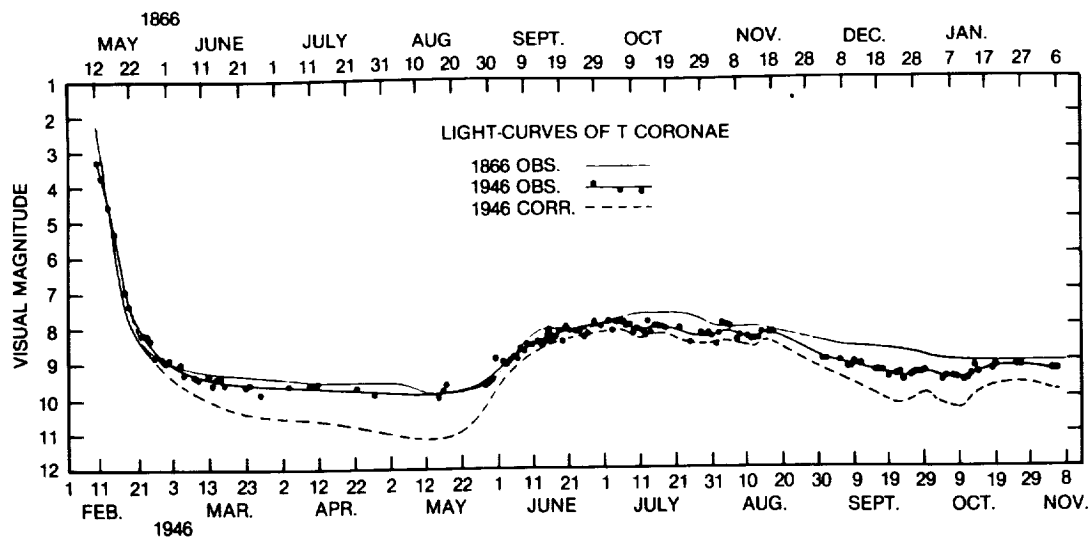


Figure 9-46. The light line is the mean light-curve for the year 1866. The heavy line is the mean light-curve for the year 1946 representing the observational points. The heavy dashed line is the 1946 curve corrected for an M-type companion of magnitude 10.2. The first point for February 9, is an observation by Armin Deutsch. (from Pettit, 1946).

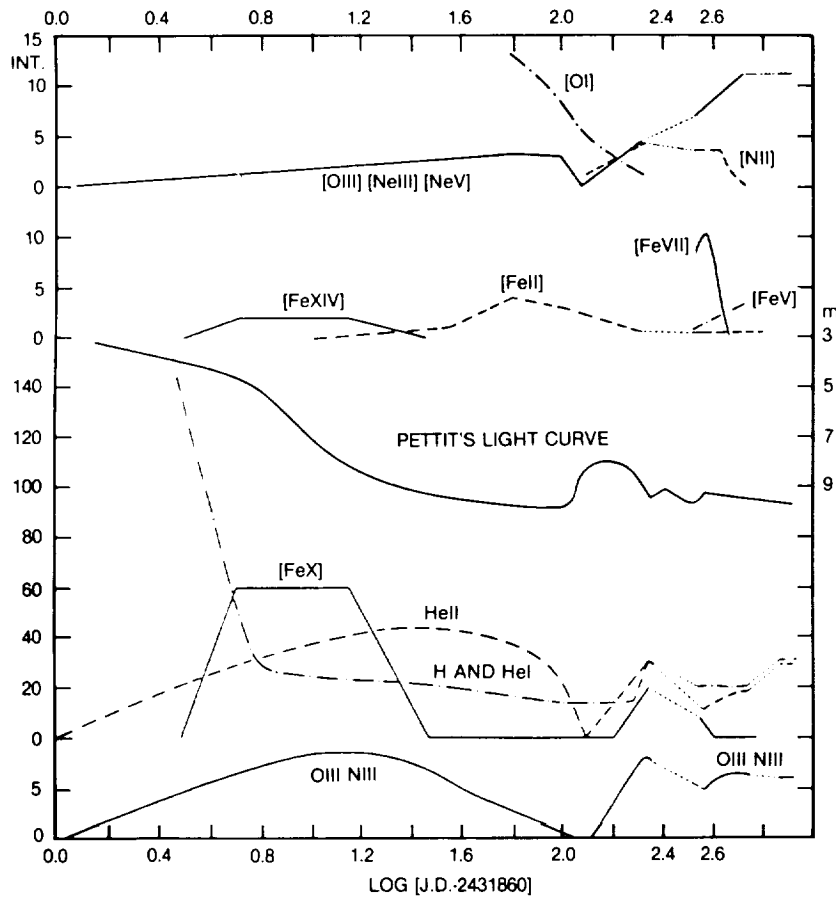


Figure 9-47. Curves of intensity for emission lines in T CrB. Abscissae are logarithms of the number of days after JD2431860. Ordinates are intensities by comparison with He 4686, assigned intensity 10. Curves for [Fe X], He II, H, and He I have ordinates compressed to one-quarter the scale of the other curves. Dotted lines join successive observing seasons. The magnitude scale for Pettit's light-curve is on the right. (from Sanford, 1949).

of some symbiotic stars in outburst, like, for instance, CH Cyg (however, which, does not show high-excitation lines).

Moreover, in slow classical novae the deep minimum is due to dust enveloping the system, as shown by the infrared observations. In the case of T CrB, on the contrary, during the interval between principal and secondary maximum, the spectrum of the M3 giant is clearly visible and not veiled by dust.

The temporary presence of coronal lines seems to be a common characteristic of recurrent novae: they have been observed in T CrB, in RS Oph, and in T Pyx. The only exception is U Sco where no forbidden lines, either of low or

high excitation have been observed, and V 1017 Sgr, however, which has several characteristics of symbiotic rather than nova.

During the outburst of 1946, T CrB brightened from $m_v \approx 9.6$ to $m_v \approx 3.0$, with an increase of a factor of 500 in luminosity. The relation $F_\lambda(\text{vis}) = 3.68 \times 10^{-9} \times 10^{mv/2.5}$ gives $F_{\lambda\text{Outb}}(\text{vis}) = 2.3 \times 10^{-10}$ (erg cm⁻² s⁻¹ Å⁻¹) at maximum. With a distance of 1300 pc, $L_{\text{Outb}}(\text{vis})$ is therefore of the order of 4.6×10^{37} erg s⁻¹ Å⁻¹. This value sets a lower limit for the bolometric luminosity during outburst: $L_{\text{Outb}} \gtrsim 10^{38}$ (erg s⁻¹). The luminosity at maximum was, therefore, close to that of 2×10^{38} erg s⁻¹, corresponding to the Eddington limit for a $1.5 m_\odot$ star.

VI.B. T CRB IN QUIESCENCE

The optical spectrum of T CrB is a typical M3 III dominated by strong TiO absorption bands. A major step in the understanding of the nature of T CrB was the discovery of its binary nature (Kraft, 1958). The radial velocity data, revised by Paczynski (1965), indicate a double-line spectroscopic binary with $P \approx 227.6$ and $m_{\text{hot}} > 1.6 m_{\odot}$ and $m_{\text{giant}} > 2.2 m_{\odot}$ (Figure 9-48). These values, however, might be affected by the uncertainties in the determination of K_2 .

Recently, a series of new spectra has been obtained by Kenyon and Garcia (1986) with the purpose of obtaining an improved orbital solution. In this study they have substantially confirmed the K_1 value without attempting, however, to redetermine K_2 , whose measurement is made

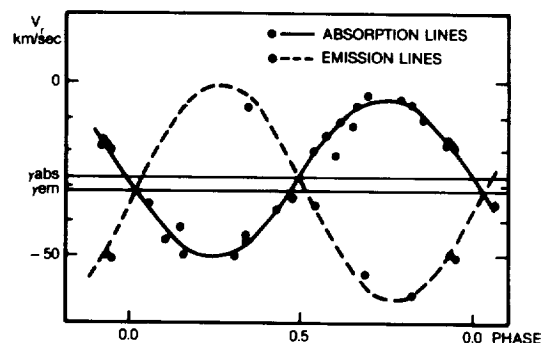


Figure 9-48. The radial velocity curves for T Coronae Borealis.
(from Paczynski, 1965).

quite difficult by the composite structure of the H emissions. In their spectra, in addition to the typical lines of the M giant, strong hydrogen, He I, and [Ne III] 3868 emissions were present (Figure 9-49). The spectra obtained by Blair et al. (1983), instead, do not show He I emissions. This

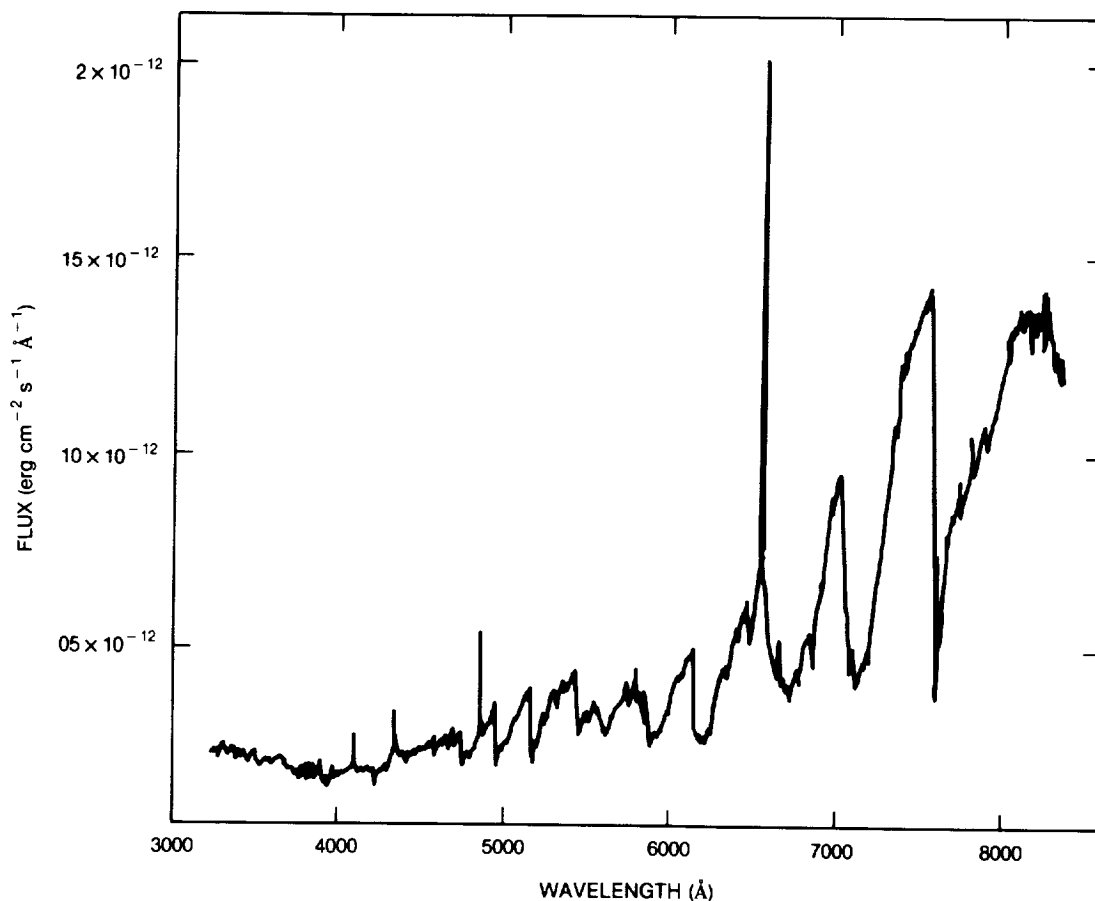


Figure 9-49. Optical spectrum of T CrB. TiO absorption bands and H I emission lines are very prominent on this April 1984 spectrum.
(from Kenyon and Garcia, 1986)

behavior indicates variations in the excitation conditions, related to changes in the temperature of the hot component. Similar variations in the spectrum were noticed and described as early as in the late thirties and in the forties by several authors (e.g., Joy 1938, Swings and Struve 1941, 1943).

The first time-resolved photometric observations during quiescent phases have detected rapid variations in the U light (M.F. Walker 1954). The star was reobserved several years later (1975) by A.R. Walker (1977), who detected a U flickering with a time scale shorter than 15 s and variations of about 0.5 magnitudes from the mean level (Figure 9-50). Bianchini and Middletich (1976) also found comparable UV flickering at nearly the same period, but they reported a marked absence of such activity for 1976. A similar behavior has been reported also by Oskanyan (1983).

These variations are very similar to the flickering exhibited by many dwarf novae that are known to have a white dwarf as companion.

A consequence of the RV observations of Kraft (1958) and Paczinsky (1965), which indi-

cated that the secondary was a main-sequence star, was to rule out thermonuclear runaway models for the outburst of T CrB. After the study by Paczinski and Sienkiewicz (1972), who found that Roche lobe overflow from a giant with a deep convective envelope could lead to extremely high \dot{M} on a (very short) dynamical time scale, Plavec et al. (1973) suggested that T CrB was in a rapid phase of convective mass-loss and that the outburst was caused by the interaction between the mass-accreting star and the large amount of material falling on it. The two historical outbursts were, therefore, attributed to two episodes of extremely high mass transfer triggered by an instability in the red giant.

Webbink (1976) has considered in greater detail the outburst behavior of T CrB and has also interpreted the outburst in terms of episodic accretion phenomena from a giant onto a main-sequence star. He suggested that the outburst was caused by the transfer of a burst of matter ejected by the giant and by the subsequent dissipation of the excess energy of this parcel of transferred mass (of $5 \times 10^{-4} M_{\odot}$) when its originally eccentric orbit around the secondary is made circular dynamically by supersonic collisions within the

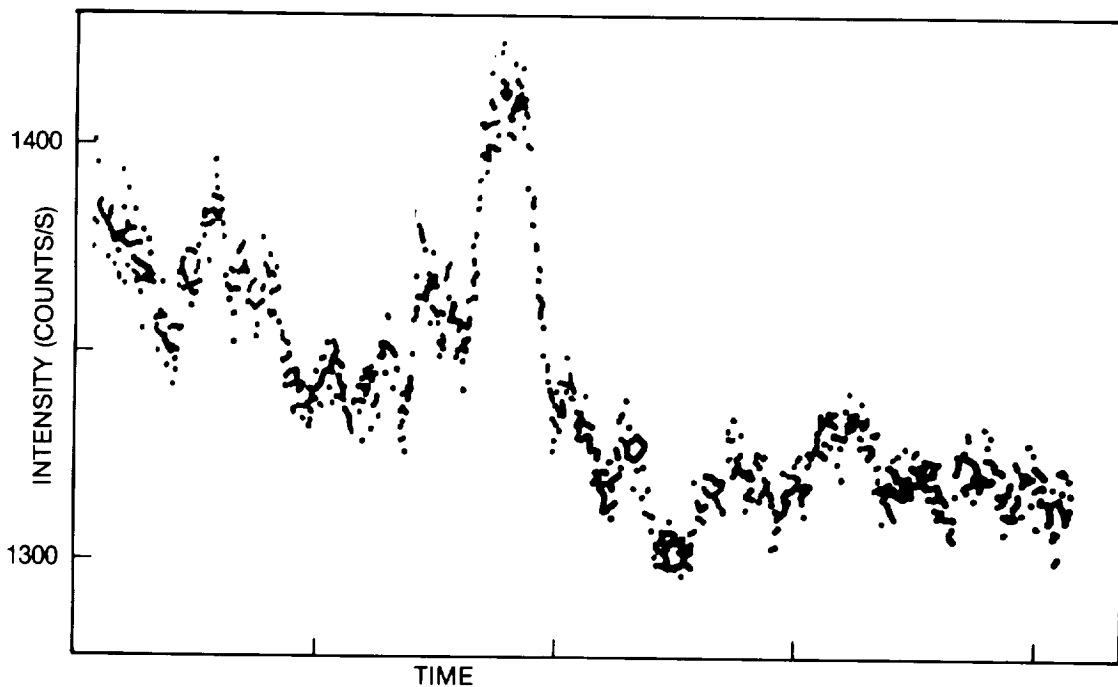


Figure 9-50. Light curve of T CrB through a U filter. The data have been corrected for extinction and the sky background has been removed. Time marks are 1000s apart. The observation was made on JD2442578. (from Walker, 1977).

orbiting material, thus producing a ring. The secondary maximum, instead, is produced when the inner edge of the disk (produced by the broadening of the ring by viscous dissipation) strikes the surface of the (main-sequence) accreting star.

With this model Webbink (1976) was able to explain the presence of the two maxima in the light curve, the time interval between them and their relative amplitude. Spectroscopic observations made at the time of the second maximum have shown, however, the appearance of a "shell" absorption spectrum and the weakening or disappearance of the emission lines (including He II 4686) in disagreement with the increase in excitation (especially in He II) expected on the basis of Webbink's (1976) explanation of the secondary maximum. Additional considerations in favor of an accretion event onto a main-sequence star as responsible for the outburst of T CrB have been reported in the extensive study on the nature of recurrent novae by Webbink et al. (1987).

After Webbink (1976), Livio et al. (1986), Starrfield et al. (1985), and Webbink et al. (1987) consider (in general) both accretion events onto main-sequence stars and thermonuclear runaways on white dwarfs as possible mechanisms for the outbursts of recurrent novae. The accretion model appeals to dynamical phenomena, similar to those proposed by Webbink (1976), to reproduce the very rapid rise of the light curve in outburst in some recurrent novae. These accretion-powered novae require shock-type events to produce the observed super Eddington luminosities and the very-high-excitation coronal-line emission observed during decline.

Thermonuclear runaways models, instead, require a very massive ($m_{\text{WD}} \approx 1.38 m_{\odot}$), low-luminosity ($L \approx 0.1 L_{\odot}$) white dwarf, and a very high accretion rate ($> 1.7 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$) to produce thermonuclear runaway outburst with the short recurrence time scales compatible with those observed in recurrent novae ($\leq 10^2$ years).

Under the above conditions, an accreted envelope mass as low as $5 \times 10^{-7} M_{\odot}$ (much

smaller than in normal classical novae, $10^{-5} M_{\odot}$) is sufficient to trigger a thermonuclear runaway (Starrfield et al., 1985). For more details about these models, the reader is referred also to Kenyon (1988), and Livio (1988a).

The above constraints reported on \dot{M} and on M_{env} have been used by Webbink et al. (1987) to define some criteria which would enable observers to distinguish between accretion-powered and thermonuclear runaway-powered recurrent novae: 1). The required high \dot{M} implies that thermonuclear runaway-powered recurrent novae must have high-accretion rates ($> 1.7 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$) and, therefore, high-accretion luminosities ($L_{\text{accr}} > 100 L_{\odot}$) at minimum. Because of the presence of a white dwarf accretor, the bulk of this luminosity is emitted in the UV, and therefore thermonuclear runaway-powered recurrent novae are expected to be luminous UV sources and to display high excitation emission lines (He II, CIV, N V) in their UV spectra.

2) Unlike most classical novae, thermonuclear-runaway-recurrent novae are expected to be emission-line objects at maximum of the outburst because the envelope mass at the time of the runaway is less massive than in classical novae.

Webbink et al. (1987) have used these two "criteria" to give additional arguments against the presence of a white dwarf in T CrB. In particular, from the weakness of the UV spectra they have examined, they have derived a \dot{M} of $10^{-6} M_{\odot} \text{ yr}^{-1}$ for a main-sequence star (or of $10^{-8} M_{\odot} \text{ yr}^{-1}$ for a white dwarf, a value too low, in their opinion, to refuel a thermonuclear runaway model with a recurrence time of 80 years).

Recently, Selvelli, Cassatella, and Gilmozzi (1990) have described the results of 9 years of UV observations of T CrB with the IUE satellite. The main conclusion of this study (which is briefly reported in the following paragraph) is that the overall behavior of T CrB in the UV (and also in the other spectral ranges) finds a self-consistent interpretation in terms of accretion onto a (massive) white dwarf.

VI.C. UV OBSERVATIONS OF T CrB

Previous studies on IUE spectra of T CrB have been presented by Krautter et al. (1981), Kenyon and Webbink (1984), Kenyon and Garcia (1986). Kenyon and Webbink have made an attempt to fit the form of the observed continuous-flux distribution to their synthetic spectra, but were unable to find a consistent model in light of the variability. Their conclusion was that accretion disks around a white dwarf or a main-sequence star could not give a consistent explanation for the UV continuum of T CrB as a function of time. Kenyon and Garcia (1986), instead, excluded the presence of a white dwarf on the basis of the relatively flat UV continuum they observed and of the overall weakness of the high-excitation lines. Tentatively, they ascribed the observed UV variations (IUE) to fluctuations within an optically thin disk orbiting a main-sequence star, fueled by matter streaming from a lobe-filling M3 III star at $10^{-6} M_{\odot} \text{ yr}^{-1}$.

Selvelli, Cassatella, and Gilmozzi (1989) have observed T CrB with IUE from the early days of IUE's life until very recently. Some short progress report of this study have been presented by Cassatella et al. (1982, 1986); Gilmozzi et al. (1987), and Selvelli et al. (1988).

VI.C.1. THE UV CONTINUUM

After correction for reddening, $E(B-V) = 0.15$, the continuum can be represented, at the various epochs, by a single power-law spectrum $F(\lambda) = A\lambda^{-\alpha}$ over the entire IUE range. The UV spectral index α ranges from 0.7 to 2.0, with a mean value of 1.25. Some examples of the continuum variability are provided in Figure 9-51. The flat spectrum corresponds with a minimum in the UV flux

(March, 1979).

In general, when the flux is high, the continuum becomes steeper. One should note that the Balmer emission continuum (peaking around 2800 - 3200 Å in the IUE range) is not negligible in T CrB (Kenyon and Garcia, 1986) and could substantially distort the shape of the long wavelength IUE spectra, causing the derived power-law index to appear flatter, at least when the object is weak (see also Figure 9-52).

The UV continuum from 1200 to 3200 Å is variable by a factor of up to 10.

Certainly, a distinctive peculiarity of T CrB is the lack of significant optical variations (as calculated from the FES-Fine Error Sensor-instrument onboard IUE) correlated to the UV ones. In particular, at the time of the UV minimum (March 1979), the FES magnitude was 9.9, while during the UV maximum of May 1983, the magnitude was 10, indicating that the bulk of the variability is restricted to the UV, in agreement with observations by Walker (1977), Bianchini and Middleditch (1976), and Oskanyan (1983), who could detect variability only in the ground U band. Also the "flares" reported for the years 1963 and 1975 by Palmer and Africano (1982) were present in the (ground) U only.

The changes in the continuum show no obvious dependence on the orbital phase. The deepest minimum (March 1979) occurred at phase ≈ 0.34 . Near phase 0.50 (red giant in front), possible occultation effects could be present. However, at phase 0.48 and at phase 0.54 no decrease was observed.

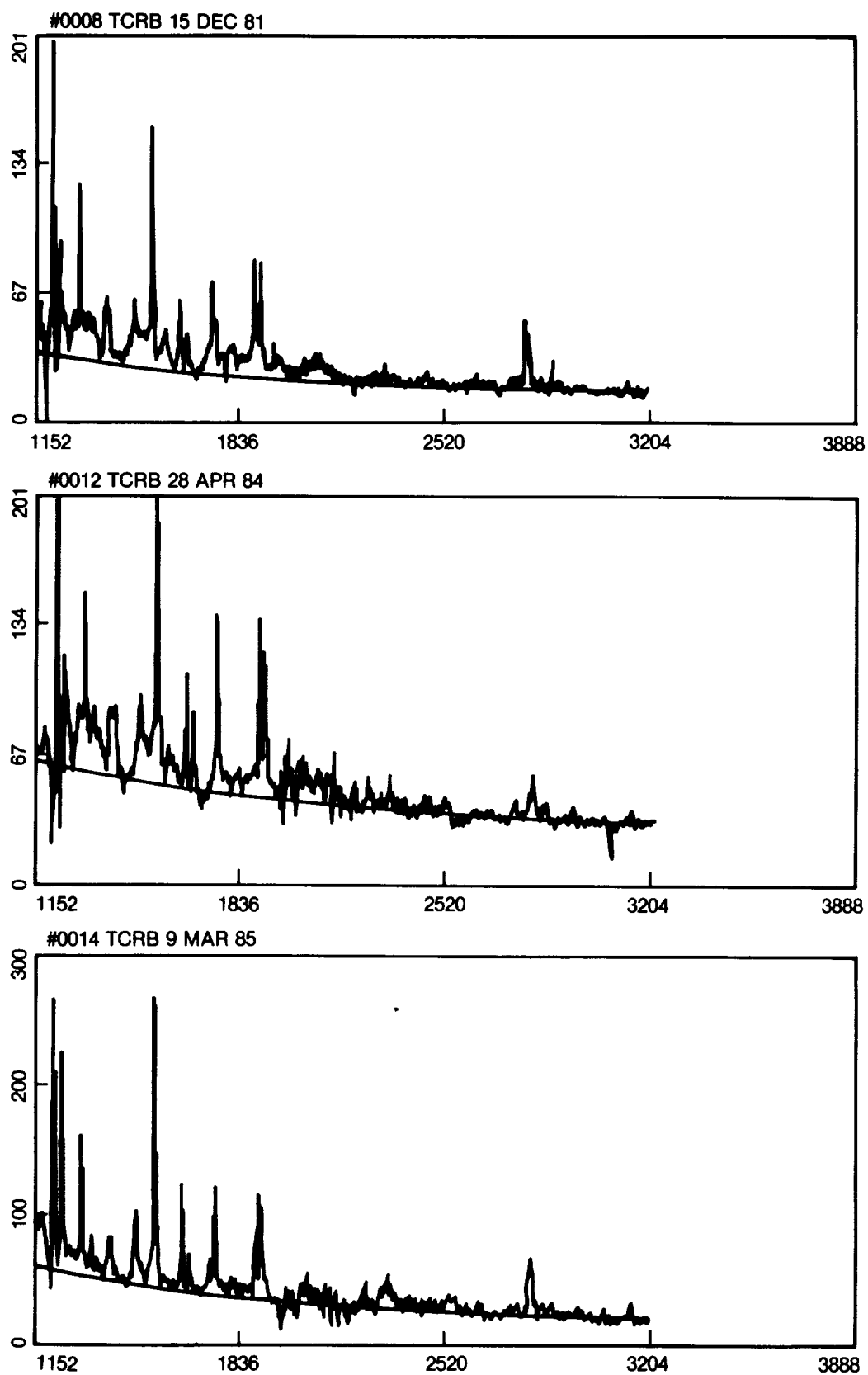


Figure 9-51. The spectrum of T CrB in three different epochs. The power-law ($\lambda^{-\alpha}$) fits of the continuum have $\alpha = 0.60$, 0.65 , and 1.0 (from top to bottom).

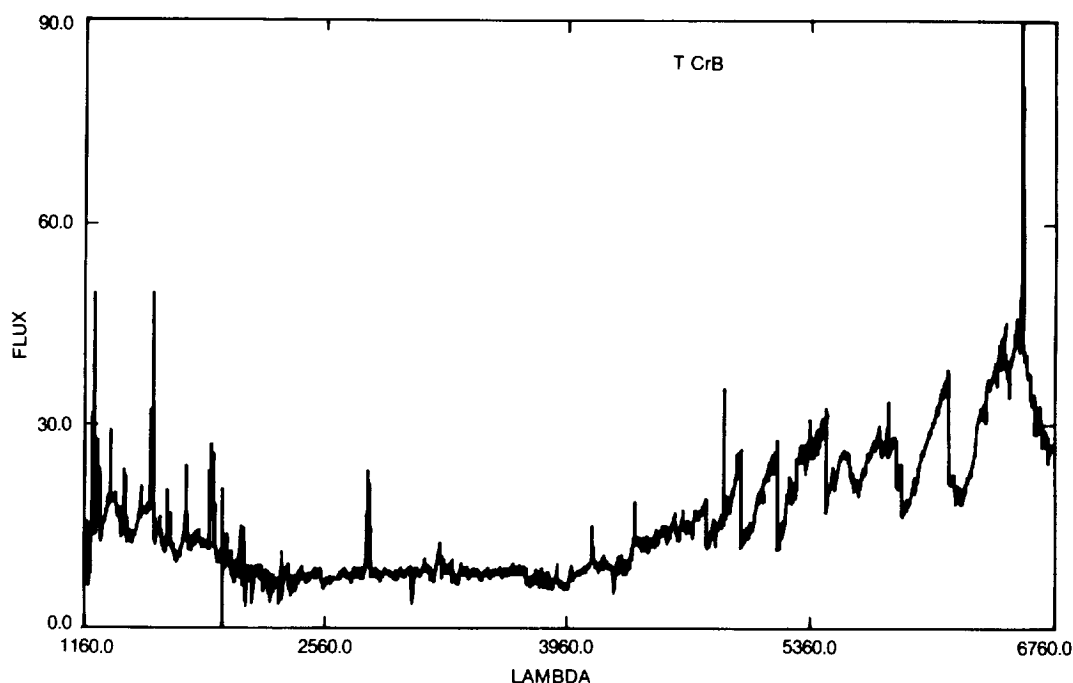


Figure 9-52. A composite spectrum of T CrB from $\lambda 1200$ to $\lambda 5700$.
(from Cassatella et al., in preparation).

V1C.2. THE EMISSION LINES

A typical UV spectrum of T CrB is shown in Figure 9-53. The emission lines are remarkably intense in comparison with classical novae in quiescence and include strong intercombination transitions (e.g., Si III, C III, N IV, O III, etc.) and the Mg II doublet, which are usually absent in classical novae.

Table 9-2 lists the most important emission lines observed in the UV spectrum of T CrB. Most lines are straightforwardly identified and are typical of symbiotic stars.

Figure 9-54 shows the time variability of the continuum and of the strongest emission lines. It is evident that the variations of the emission lines, both of low and high degree of ionization, are correlated with the continuum variations, showing as well no dependence on the orbital phase. This suggests that photoionization is the main energy input mechanism, as in the symbiotic stars Z And, AG Car, and HBV 475, and unlike in CH Cyg. The general lack of significant changes in the line fluxes near phase 0.5 seems to

rule out the possibility of a partial eclipse of the hot component (which would be most readily detected in the emission lines because of their origin in a larger region than the continuum).

There is marginal indication, in some spectra, of a possible P Cygni profile in the NV line, although it cannot be excluded that this effect is only apparent and due to the Ly α being either variable in width or not filled in, at these epochs, by the geocoronal Ly α . If true, the P Cygni profile would indicate an outflow velocity larger than 2000 km/s, in analogy to the case of AG Dra (Viotti et al., 1984).

High-resolution spectra, although partially underexposed, clearly indicate that the high-excitation lines (C IV 1550, He II 1640) have a shallow and broad profile (HWZI ≥ 1000 km/s). The Si III λ 1892 and C III λ 1909 emissions have instead narrow cores and broad wings. The FWHM corresponding to the broad components are comparable to the ones derived by Kraft (1958) for the H β line (330 km/s), while the narrow component is only instrumentally broadened.

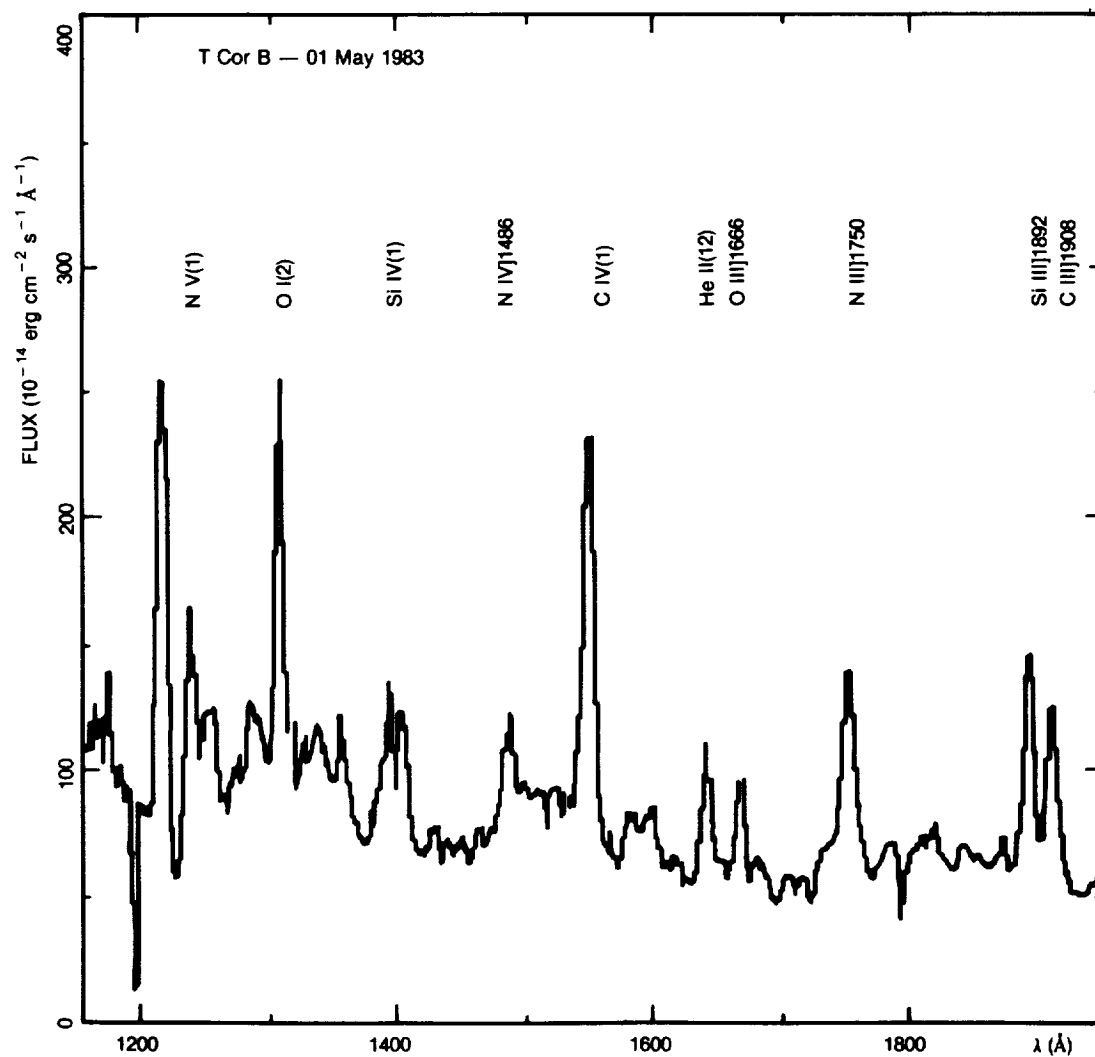


Figure 9-53. A short wavelength IUE spectrum of T CrB taken on May 1, 1983, with typical emission lines. The high excitation NV line is a prominent feature.

TABLE 9-2 THE UV EMISSION SPECTRUM OF T COR B

	Identif.		
1240	NV (1)	1665	OIII
1285	?	1750	NIII (0.07)
1304	OI (2)	1892	SiIII (1)
1335	CII (1)	1908	CIII (0.01)
1355	OI (1)	2330	CII + SiII
1400	SiIV (1) (+OIV)	2670	AlII (1)
1485	NIV (0.01)	2735	HeII
1530	?	2800	MgII (1)
1550	CIV (1)	2835	OIII (Bowen)
1594	?	3133	OIII (Bowen)
1640	HeII (12)	3188	HeI (3)

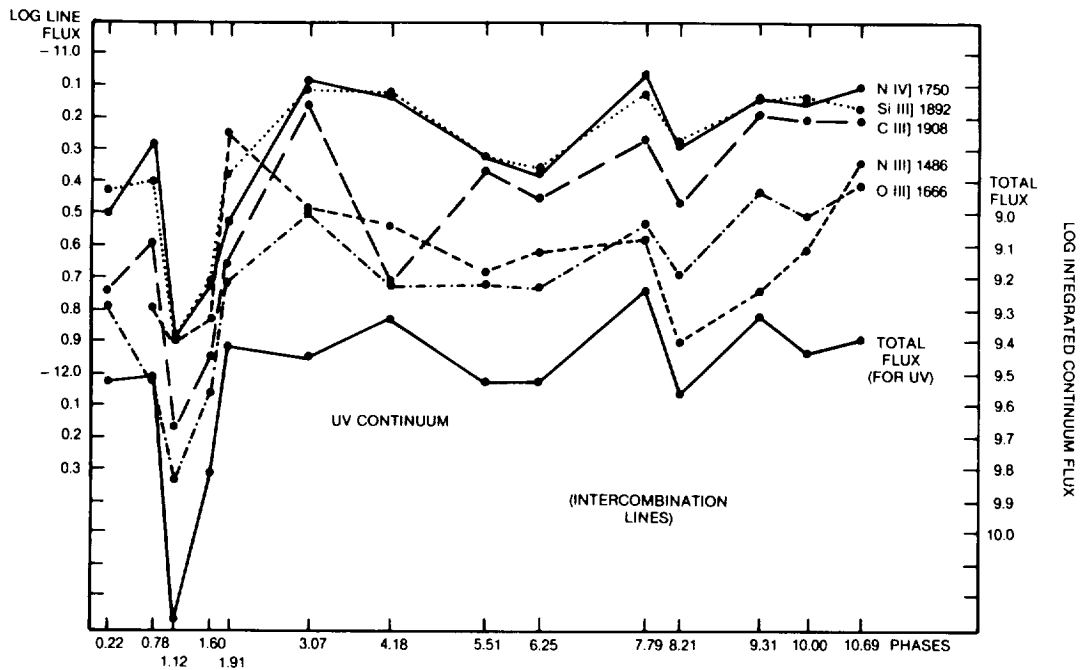


Figure 9-54a. Time variability of the emission line fluxes and of the integrated continuum flux 1152-3200 Å from 1978 to 1985. A deep minimum occurred in March 1979. Intercombination lines.

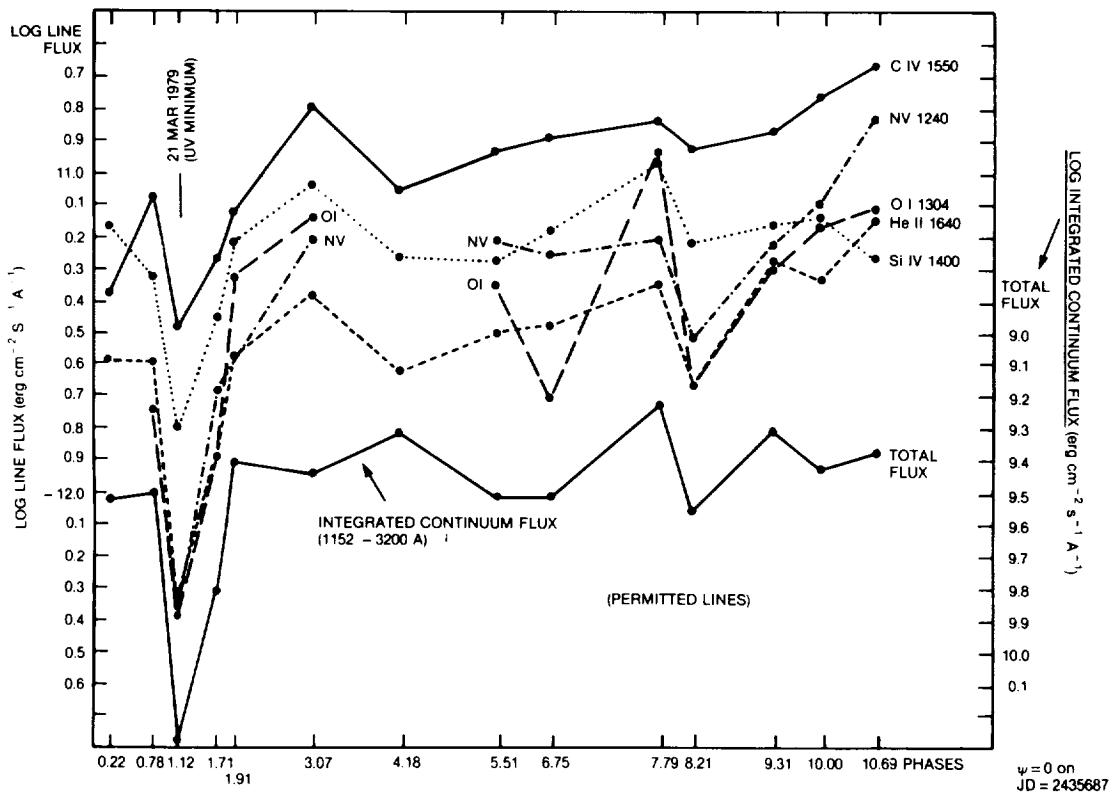


Figure 9-54b. Same as Figure 9-54a. Permitted lines.

VI.C.3. THE ABSORPTION LINES

Absorption lines are generally present in all the spectra of T CrB, although their intensity has shown considerable variations with time.

The overall UV absorption spectrum of T CrB is, at some epochs, very similar to that of late B and early A supergiants, with lines mainly of once-ionized metals (Fe II, Ni II, Cr II...). This seems to be a typical signature of symbiotic stars during activity phases and mimics an optically thick cool shell surrounding the hot component (Sahade and Wood, 1978). Kenyon (1986) has also reported recently a similar behavior for the symbiotic star PU Vul.

A high-resolution, near ultraviolet (2000-3000 Å) spectrum obtained on April 30, 1982, has confirmed the presence of many absorption lines from once-ionized metals (mainly Fe II).

VI.D. THE HYDROGEN RECOMBINATION CONTINUUM

The hydrogen free-free and free-bound emissions are generally an important component of the observed UV energy distribution in symbiotic stars with which T CrB has been sometimes associated. A determination of this contribution is not, in general, possible for the lack of simultaneous optical and UV observations. However, for the epoch February 1981, a rough estimation can be made from the observed H β flux ($1.05 \cdot 10^{-12}$ erg cm $^{-2}$ s $^{-1}$, Blair et al. 1983) in the assumption that the emitting volumes are the same. This gives an expected flux at 2800 Å of 5.3×10^{-15} erg cm $^{-2}$ s $^{-1}$ Å $^{-1}$, a value below the IUE detection limit for the exposure time used.

On the other hand, Kenyon and Garcia (1986), have obtained optical spectra in which the Balmer jump is clearly present in emission. This is confirmed by recent UV and optical spectra (Casatella et al. 1988). Probably, the recombination continuum is either variable or it was masked by the strong far UV component during the high state of February 1981.

VI.E. DIAGNOSTICS

VI.E.1. THE ELECTRON DENSITY

The electron density in the line-emitting region has been derived from the intensity ratio of the Si III] 1892 and C III] 1909 intercombination lines, both strong in the spectra of T CrB. Calculations of the Si III]/C III] ratio from Nussbaumer and Stencel (1987) were adopted. In addition, it was assumed that

- (1) The ionization fraction $[N(\text{Si III})/N(\text{Si I})]/[N(\text{C III})/N(\text{C I})]$ is about 0.5.
- (2) The Si and C abundances are solar.
- (3) The electron temperature of the emitting region is 15000 K (see following).

The mean value of the electron density since January 1979 is 2.8×10^{10} cm $^{-3}$. The highest density (1.2×10^{11} cm $^{-3}$) corresponds to the peculiar spectrum of February 1981, while the lowest value (1.8×10^{10} cm $^{-3}$) is recorded on March 9, 1985.

An independent estimate of the electron density can be made using the N III] multiplet around 1750 Å, whose line components could be detected in two high-resolution spectra. From the measured fluxes of these lines, and the calculations by Altamore et al. (1981), it results $N_e = 1.7 \times 10^{10}$ cm $^{-3}$ on June 1980, and $N_e = 1.3 \times 10^{10}$ cm $^{-3}$ on February 1981, in agreement with the low-resolution estimates.

VI.E.2. ELECTRON TEMPERATURE

The electron temperatures of the line-emitting regions can be determined from the low-resolution spectra by making use of the N IV 1718 / N V 1240 and the C III 1176 / C III] 1909 flux ratio between lines produced by dielectronic recombination and lines produced by collisional excitation, following the calculations by Nussbaumer and Storey (1984).

The measured line ratios, corrected for reddening, and the derived electron temperatures give a mean value of about 13000 K \pm 1000 K.

The C III 1176 / C III] 1909 flux ratio provides values which are systematically higher than those derived from the N IV 1718 / N V 1240 ratio.

Note, however, that the C III 1176 emission falls near the camera sensitivity cutoff, and it is, therefore, difficult to measure accurately.

VI.E.3. DETERMINATION OF \dot{M} FROM THE UV LUMINOSITY

Accretion onto a compact object is a commonly accepted mechanism for producing the observed UV luminosity in Cataclismic Variables. In most cases (semidetached systems), the mass transfer is achieved through Roche-lobe overflow but wind accretion can also be effective, especially for detached systems containing a mass-losing primary. In the absence of (strong) magnetic fields, matter accretes on the compact object forming an accretion disk. Mass loss can be estimated if the disk luminosity and the nature of the accreting object are known or assumed. In this case $\dot{M} = 2RL/GM$, where R and M refer to the accreting object.

This value of \dot{M} is not model-dependent but requires the knowledge of the bolometric accretion luminosity. In general, therefore, it underestimates the mass-loss accretion rate if only a limited spectral range is available. Assuming a distance to T CrB of 1300 pc, the reddening corrected IUE integrated luminosity ranges from 2.6×10^{34} erg/s (21 March 1979, deep minimum) to 2.6×10^{35} erg/s (1 May 1983, maximum). An average value of the integrated UV luminosity is 2.2×10^{35} erg/s. The IUE observations have shown that the disk luminosity is radiated mostly in the UV with a negligible contribution to the optical. This is a strong indication in favor of a white dwarf accretor: a main sequence accretor is expected to emit mostly in the optical region in contrast with the observed behavior of T CrB.

The presence of a quite strong He II 1640 emission requires a very hot continuum with a temperature of the order of 10^5 K. This value also is hardly compatible with a main-sequence

accretor and suggests in itself the presence of a compact accreting object (see also the following sections). Taking indicative values of a white dwarf ($M = 1 M_{\odot}$ and $R = 0.01 R_{\odot}$), the derived accretion rate is $\dot{M} = 4 \times 10^{-8} M_{\odot}/\text{yr}$ ($= 2.5 \times 10^{18}$ gr/s.) An independent check for \dot{M} can be made through the \dot{M} - $\lambda 1640$ intensity relation given by Patterson and Raymond (1985b). Their Table II gives $\dot{M} \approx 10^{19}$ g/s for $L(1640) = 10^{33}$ erg/s and $M = 1 M_{\odot}$ for the white dwarf, in good agreement with our estimate based on the UV continuum. The same model gives, for this \dot{M} , a boundary layer temperature of about 4×10^5 K with a luminosity of 10^{36} erg/s.

VI.E.4. THE ZANSTRA TEMPERATURE FROM HE II 1640

The He II 1640 emission, as a recombination line of an ion requiring 55.4 eV for ionization, is an unambiguous and useful indicator for the presence of high-energy radiation in the spectrum. This line, together with the $\lambda 4686$ emission, has long been known as a typical signature of X-ray binaries (Patterson and Raymond, 1985a). It is remarkable that $\lambda 1640$ is often absent in dwarf novae (Szkody, 1985), while it is present in AM Her stars and intermediate polars.

Because of the high energy of its lower level, it is unlikely that the He II 1640 line is formed by a mechanism other than recombination after radiative ionization. This seems indeed to be the case of T CrB, as indicated by the positive correlation between the He II 1640 and the UV continuum fluxes. Whatever the nature of the ionizing source is, it is possible to estimate its temperature using the Zanstra method under the assumption that the ionizing source radiates as a blackbody and that the He II emitting region is optically thick to the continuum of the blackbody source shortward of 228 Å (ionization limit of He II). With the assumption that the reddening corrected flux of T CrB at 1300 Å, $F(\lambda 1300)$ is entirely contributed by the blackbody source, the flux ratio $F(\lambda 1640) / F(\lambda 1300\text{Å})$ provides a direct indication of the Zanstra temperature (see, e.g., Pottash, 1985). The He II Zanstra temperature

was substantially constant over the period covered by the UV observations: $T(Z) = 66000$ K, on average.

Because of the assumptions implicit in the definition of the Zanstra temperature, the above value is actually a lower limit to the temperature of the ionizing source.

VI.F. THE EUV/SOFT X-RAY LUMINOSITY

The 1640 intensity can be used to determine the number of photons with energies higher than 55.4 eV, to provide an estimate of the EUV/soft X-ray flux in T CrB. The average value of the He II 1640 line intensity is 5×10^{-12} erg s⁻¹ cm⁻². Since the distance to T CrB is 1300 pc, the average $\lambda 1640$ luminosity is 1.3×10^{33} erg/s. Assuming case B recombination and assuming that all EUV photons are able to ionize He II, it is possible to estimate the number Q_4 of photons with energies higher than $4h\nu = 55.4$ eV (See also Pottasch, 1985):

$$Q_4 = \int_{4\nu_0}^{\infty} \frac{L_\nu d\nu}{h\nu} = \frac{\alpha(B, \text{tot})}{\alpha(\text{eff})} \frac{He^{++}}{1640} \frac{L(1640)}{h\nu(1640)}.$$

Taking $\alpha(B, \text{tot}) = 2.6 \times 10^{-13}$, $\alpha(\text{eff } 1640) = 8 \times 10^{-14}$, $h\nu(1640) = 7.5$ eV, it results that $Q_4 \approx 3.3 \times 10^{44}$ photons. Assigning an average typical energy of 100 eV to these photons, the obtained luminosity is about 5×10^{34} erg/s. This is, however, a lower limit for $L(\text{EUV})$, since it seems unlikely that all photons ionize He II and also that we are in a spherically symmetrical situation. A value of a few 10^{35} erg/s seems realistic ($\sim 100 L_\odot$).

From this, one can obtain a rough (but indicative estimate of the dimensions of the region involved from the simple relation $L = 4\pi R^2 \sigma T^4$ with $T \sim 10^5$ K; $R \approx 1.2 \times 10^4$ Km. It is tempting to relate this value to a region associated with a white dwarf.

VI.G. THE RELATIVE OPTICAL+UV+X-RAY CONTRIBUTION TO THE TOTAL LUMINOSITY

The hot component (disk) luminosity contrib-

utes to the satellite UV mostly. At some epochs (Bianchini and Middleton, 1976; Walker, 1977; Oskanyan, 1983) there has been a contribution by the hot source to the ground U at best, but never to the B or V, as confirmed also by the FES photometry that has shown no correlation with the significant far UV variations. On the other hand, if the observed far UV continuum slope ($\lambda^{-\alpha}$ with $\alpha = 1.2$ on the average) is extrapolated toward the visible, a contribution of a few percent to the giant optical luminosity ($100 L_\odot$) is expected and should be detectable by the FES photometry. Evidently, the above power-law approximation breaks down at longer wavelengths, probably because the disk becomes optically thin in its cooler outermost layers, thus truncating its contribution to the optical. In practice, the disk-hot component emits only in the satellite UV and, at some epochs, in the ground U, while the giant emits mostly at longer wavelengths.

It is remarkable that the soft x-ray luminosity, as estimated from the He II emission intensity gives a power comparable to that of the UV:

$$L(\text{disk}) \geq 2 \times 10^{35} \text{ erg/s} = L(\text{UV})$$

$$L(\text{EUV—soft x}) \geq 10^{35} \text{ erg/s}; L(\text{hard x}) \approx 10^{31} \text{ erg/s}.$$

VI.H. THE NATURE OF THE COMPANION

A white dwarf companion has been explicitly or implicitly assumed in the previous considerations. There are, in fact, several observational indications which are hardly compatible with the presence of a main-sequence companion:

- 1) The bulk of the disk luminosity is emitted in the UV, with a negligible contribution in the optical range ($L(\text{UV}) \sim 2 \times 10^{35}$ erg/s and $F_\lambda(\text{UV}) \sim \lambda^{-1.2}$). This UV luminosity is larger than that found in old novae. It is difficult to explain at the same time this UV luminosity and its spectral distribution with a main sequence accretor, because this would require a very high accretion rate and, as a consequence, the disk would emit mostly in the optical, contrary to what is observed. With the white dwarf assumption, the observed UV

continuum luminosity (a lower limit of the total disk luminosity) gives $\dot{M} \geq 2.5 \cdot 10^{18}$ gr/s. 2) A rather strong He II $\lambda 1640$ emission is generally present: $L(1640) \approx 1.2 \cdot 10^{33}$ erg/s. (N V is also present, although weaker). These emissions are indicative of temperatures of the order of 10^5 K, and are naturally associated with the boundary layer. The semi-empirical estimates of Patterson and Raymond (1985), who assume a white dwarf, associate to this He II 1640 luminosity a mass-accretion rate of 8×10^{18} gr/s, in good agreement with that derived directly from the UV luminosity. It is also remarkable that only a white dwarf accretor, at the calculated \dot{M} , can explain at the same time both the observed UV luminosity and the high temperature required to produce the He II 1640 emission intensity.

3) The X-ray luminosity (Cordova, et al., 1981) from the Einstein satellite in the range 0.2-4.5 KeV is $L = 5 \times 10^{31}$ erg/s, of the same order of that found in the X-ray brightest old novae (mean value 6×10^{31} erg/s from Patterson and Raymond, 1985a).

4) The EUV luminosity emitted below $\lambda 228$ Å, as estimated from the He II 1640 emission is $\geq 5 \times 10^{34}$ erg/s, that is, comparable with the observed UV luminosity $L(\text{UV}) \approx 2 \times 10^{35}$ erg/s. If $L(\text{UV})$ is attributed to the disk and $L(\text{EUV})$ to the boundary layer, it is evident that the power emitted by the disk is on the same order of magnitude as that emitted by the boundary layer, in agreement with the theoretical predictions for a "standard" disk around a white dwarf accretor (Patterson and Raymond, 1985b). They also predict that when \dot{M} is larger than 10^{16} gr/s, then only a small fraction of the bolometric luminosity is emitted as "hard" X-rays (0.2-4.5 KeV), as actually observed, (point 3: $L_x \approx 1.5 \cdot 10^{31}$ erg/s).

5) The shape of the C IV 1550 (and He II 1640) emission lines in high-resolution spectra is very wide and shallow. C IV, the strongest UV line in low-resolution spectra, is hardly evident at high resolution, while weaker lines (e.g., the semi-forbidden lines of C III and Si III) are sharper and clearly present.

This indicates that C IV and He II are strongly broadened by rotation, probably because they originate in the innermost disk region. The (HWZI) for C IV gives $v \sin i$ larger than 1000 km/s, a value not compatible with a main-sequence star.

Two other indications for the presence of a white dwarf in T CrB are the presence of flickering (Walker, 1977; Bianchini and Middleton, 1976) and the fact that in the 1946 outburst the expansion velocity reached ~ 5000 km/s (Herbig and Neubauer, 1946), a value of the order of the escape velocity from a white dwarf.

All these arguments in favor of the white dwarf are "disturbed" by the results of the orbital data for T CrB, which suggest a mass for the companion higher than that acceptable for a white dwarf (Kraft, 1958; Paczynski, 1965).

The problem of the radial velocity is of critical importance. Radial velocity variations in the giant's lines were first noted by Sanford (1949) who proposed a period of 230 days. A subsequent investigation by Kraft (1958) led to an improved period (227.6) and to the detection of radial velocity variations also in the H emissions whose considerable width (300 km/s) together with their small velocity range ($K_2 \approx 30$ km/s), prevented Sanford to detect the radial velocity changes. Kraft used several plates for the determination of K_1 (23 km/s), but seven plates only for the detection of K_2 . Paczynski (1965), using the same data as Kraft improved the curves obtaining $K_1 = 22.9$, $K_2 = 31.3 \pm 2$, and $q = M_1/M_2 = 1.4 \pm 0.2$. Adopting $i = 68^\circ$, the results for the masses were $M_1 \approx 2.6 M_\odot$, and $M_2 \approx 1.9 M_\odot$, thus placing the hot component above the Chandrasekhar limit. This fundamental conclusion has remained unchecked since then. It must be stressed that:

1) The H emissions of T CrB are quite wide (300 km/s) and severely distorted by the absorptions of the giant and show a composite structure; are they necessarily associated with the orbital motion of the hot component?

2) An entire period of the emission lines was covered by only seven points (plates) in all.

and only two plates were close to quadratures (velocity maxima).

3) About 30 years have elapsed since these radial velocity determinations. Even nowadays, in spite of the considerable improving in the measuring techniques, the problem of how to measure K_{em} is serious and difficult. For a critical analysis of the detection of K_{em} see, for example, Wade (1985), p. 307; Shafter (1985), p. 355; and Gilliland et al. (1986).

4) Kraft himself (1958), after the laborious operations for reconstruction of the emission profile, explicitly stated (p.629) that "a non negligible degree of error might still exist in the orbit derived from the H emissions."

Under all these circumstances, an error of 8 km/s in excess for the K_2 value by Kraft (1958), whose measurement is substantially based on two points only (and of critical determination), is not unlikely. A reduction of K_2 by this amount would yield $K_1 \approx K_2 \approx 23$ km/s and a solution $M_1 \approx M_2 \approx 1.4 M_\odot$ for the masses, thus allowing the accreting object to be a degenerate dwarf near the Chandrasekhar limit.

Note that this is the sole solution compatible with $q \geq 1$, $M_2 \leq 1.4 M_\odot$ and $i = 68^\circ$ ($q = M_1/M_2$).

Recently, Kenyon and Garcia (1986) have accurately remeasured K_1 ($= 23.3$), confirming substantially the value proposed by Paczynsky (1965). They have not attempted, however, to remeasure the emission line radial velocity and, in their new determination of the orbital parameters, they either have assumed $q = 1.2$, or have used indirect methods to give evidence that $q \approx 1.3$. How can the discrepancy between the UV observations (which clearly indicate a white dwarf companion) and the radial velocity studies (which indicate a companion more massive than $1.4 M_\odot$) be reconciled? Two possible scenarios can be envisaged:

1) The radial system is triple, composed of a "normal" binary nova and the giant. The mass of the "companion" of the giant is the mass of the nova system ($M_{Tot} \approx 1.8 M_\odot$), compatible with the presence of a $0.5 M_\odot$ red dwarf

and of a rather massive ($\sim 1.3 M_\odot$) white dwarf.

2) The radial velocity results are (slightly) wrong: K_2 is smaller and of the order of $K_1 \approx 23$ km/s. In this assumption, the radial velocities would be compatible with the presence of a $M_1 \approx 1.4 M_\odot$ giant, and of a very massive ($M_2 \approx 1.4 M_\odot$) white dwarf.

It is remarkable that theoretical considerations (Starrfield et al., 1986) require the presence of a massive white dwarf in recurrent novae. It is also remarkable that the \dot{M} derived from the UV observations ($\dot{M} \approx 4 \times 10^{-8} M_\odot/\text{yr}$) is exactly that requested to produce a recurrence time of the order of 100 years (or slightly less) for the outbursts in a massive ($1.4 M_\odot$) white dwarf (Kenyon, 1988, Livio, 1988).

New, accurate, radial-velocity measurements of the emission lines associated with the hot component are clearly required. Unfortunately, in the optical most hydrogen lines are contaminated by the cool component, and the He lines are rather weak. The UV range offers a line (He II $\lambda 1640$), which is a good candidate for the measurements of K_2 ; beyond any doubt, it is associated with the hot component and, thanks to the high excitation (40.8 eV) of its lower level, it is not affected by reabsorption.

The acquisition of a series of high-resolution spectra with good signal-to-noise ratio of this line however, is, a task that only the Space Telescope can successfully perform.

VII. CONCLUSIONS

The detailed description of the observed characteristics of the five known recurrent novae proves the statement made in the first section of this chapter: They are a rather inhomogeneous group. T CrB and RS Oph are very similar: a) both have a quiescent visual spectral type M III; b) both are fast novae; c) both have spectra in outburst characterized by strong emissions and strong coronal lines; d) both have been detected with the IRAS and present a low infrared excess; e) both present variable ultraviolet spectra, but

we cannot say if their shape and variability are similar or very different—as it appears from the available observations—because T CrB has been observed for several years during its quiescent state, while only few observations have been made for RS Oph in quiescence and in outburst.

U Sco is a fast nova like T CrB and RS Oph, but has very different characteristics: Its visual spectrum at minimum is G0 V, and it does not present forbidden and coronal lines during outburst. The ultraviolet spectrum in outburst is completely flat with superposed permitted and semipermitted emissions.

T Pyx and V 1017 Sgr are both slow novae. However, this is the only common characteristic. T Pyx is a typical recurrent nova, whose outbursts are very similar to each other (and this is true also for the other recurrent novae with the exception of V 1017 Sgr), while V 1017 Sgr has presented

outbursts of different amplitudes. T Pyx has a very blue spectrum at minimum, while the minimum spectrum of V 1017 Sgr is G5 III. The spectrum of T Pyx in outburst is characterized by the presence of several strong forbidden and coronal emissions, while V 1017 Sgr presents no forbidden lines with exception of weak [Fe II] lines.

The chemical composition of the ejecta of the recurrent novae is not homogeneous, suggesting that different processes originate the outbursts. For instance, the scanty available determinations indicate that U Sco presents He and N excess, RS Oph presents N excess, while T Pyx shows no evidence of CNO excess and presents a slight deficiency of He. No data are available for T CrB and V 1017 Sgr.

The meaning of the abundances of the ejecta and their relation to the mechanisms producing the outburst have been discussed in chapter 7.

10

SUMMARY

M. Hack and M. Friedjung

We summarize here the main results and the several open questions on classical and recurrent novae, both from the observational and theoretical side.

I. THE OBSERVATIONS

The observations indicate that three main periods can be recognized in the nova phenomenon: the quiescent stage, when the object behaves like a typical dwarf nova; the outburst, when the more or less rapid increase of luminosity is accompanied by expulsion of several envelopes producing the premaximum, the principal, the Orion, and the diffuse-enhanced spectrum; and the nebular phase, when the envelope becomes sufficiently rarefied to give a pure emission-line spectrum and becomes spatially resolvable a few years after the outburst.

The space era has offered the possibility of measuring almost the whole electromagnetic spectrum of celestial objects. What has been the gain in knowledge we have obtained in the special case of novae?

As it was observed for the first time for FH Ser, the bolometric magnitude remains constant for a longer time interval or presents a much slower decline than the visual magnitude.

As we have seen in Chapter 6, ultraviolet and X-ray observations have strengthened the previous evidences that all novae are close binary systems and confirmed the presence of a white dwarf and an accretion disk in classical novae, and probably also in all recurrent novae,

although some doubt that the companion is a dwarf nova or a main-sequence star still exists for some systems (e.g., see discussion on T CrB in Chapter 9).

Infrared measurements, both from the ground and space, have clarified the reason for the presence of the dip in the light curve of slow novae, i.e., formation of dust in the ejecta, although it is not still clear which is the mechanism of formation. Several examples suggest that these mechanisms are more efficient in slow novae than in fast novae, but they seem not efficient in very slow novae like HR Del or RR Pic, which do not present any dip in their light curve.

Radio observations, together with imaging and spectroscopy have given information on the extension, shape, density, temperature, and motions of the envelope and the rate of mass loss.

There are some indications that the old nova remnants need very long time intervals to go back to the preoutburst state remaining brighter than their prenova magnitudes for several tens of years. For this reason, it is very important to find and to observe the remnants of historical novae like WY Sge 1783 and CK Vul 1670. The sensitivity of the new electronic detectors can be of great help in finding very faint traces of past outbursts. The IUE satellite has permitted us to observe several quiescent novae and to monitor some of them for time intervals sufficiently long for studying their variability, thus permitting us to detect periodical, quasi-cyclical and irregular variability.

Moreover, several outbursts of novae have been monitored with IUE. Combined optical and ultraviolet observations of novae in outburst have permitted us to derive more accurate abundances in the ejecta, because of the possibility of observing lines of several elements in different ionization states. The previous results, that CNO are enhanced, and that enhancement is generally stronger in fast than in slow novae, are confirmed: none of the novae studied with IUE have ejecta with solar abundance. A very important result is the discovery of another class of novae (Starrfield and Snijders, 1987). The members at present are three: V693 CrA 1981, V1370 Aql 1982, and Nova Vul 1984 # 2.

In V693 Cr A, all the intermediate mass elements, from nitrogen to aluminum are enhanced by a factor of about 100. In V 1370 Aql, the elements up to sulphur are enhanced, and neon is the most abundant element in the ejecta. Also Nova Vul 1984 # 2 shows a large overabundance of neon in the ejecta. Recent developments of the thermonuclear runaway theory (Starrfield et al. 1985, 1986) have shown that these observations are explained by the ejection of core material from an oxygen, neon, magnesium white dwarf. Hence, we can distinguish novae with CO white dwarfs and novae with ONeMg white dwarfs in close binary systems. The main distinguishing feature is the emission line [Ne IV] 1602. If it is present at late times in the outburst, the ejecta are neon rich (Starrfield and Snijders, 1987).

The evidence that all the well-studied objects are close binaries may explain the large variety of behavior of novae. In fact, we dispose of a larger number of parameters than one can have with a single star, and this explains, at least qualitatively, such a large variety of phenomena observed among members of a same class. However, a large number of questions must still be answered. Let us summarize some puzzling observations.

All nova systems have periods larger than 2.82 hours and shorter than 1 day with just two exceptions: CP Pup, period $P = 1.58$ hours (the only nova known to have a period below the gap) and

GK Per, $P = 1.9$ days (the only nova known to have a period longer than one day). Light curves are not exactly repeatable, and when they present minima, they are not always simply interpretable as an eclipse of the hot companion, because the epochs of the minima are sometimes varying. The variability in light curves, and especially the varying epochs of the minima both seem to validate the idea that it is the eclipse of an unstable structure like a hot spot on the accretion disk that we are observing, and not the hot star itself.

The part devoted to dwarf novae and nova-like stars shows the great similarity of these two classes of cataclysmic variables with that of these quiescent novae. Actually, several quiescent novae are members of a specific class of dwarf novae. Hence it remains an open question whether all dwarf novae have suffered or will suffer a nova outburst. We still do not know why systems with practically identical properties may or may not develop an outburst phase.

The observations that the properties of a nova before and after outburst remain the same is a proof that the outburst, although so impressive from the observational side, affects only the "skin" and not the internal structure of the system.

We can ask why the spectral and photometric characteristics of quiescent novae are so similar to each other, and why they develop such macroscopically different characteristics in outburst: very fast and very slow evolution of the outburst, expansion velocities up to several thousand km/s or a few hundred km/s, fast novae with smooth light curves, or curves presenting oscillations during the decline, slow novae with a secondary maximum, generally absent in fast novae, etc.

Why do few quiescent novae present coherent oscillations, while the majority of the others present flickering?

Why does the general rule—valid for dwarf novae—that the spectrum of the cold companion is detectable only for orbital periods greater than six hours seem not to be valid for all old novae?

Are some slight differences observed—on the average—among the spectra of dwarf novae, nova-like, and quiescent novae real? Or are they due only to the low number of observations of a same individual with highly variable spectrum? A better understanding of these phenomena could be obtained by long series of observations of a few selected objects, rather than by a few scattered observations of a large number of individuals (see, for example, the important results obtained by the long series of optical observations of GK Per—see Chapter 8—and of UV observations of T CrB—see Chapter 9).

Two important physical quantities that are badly known are the masses of the two members of a nova system. Moderately high-resolution spectra of these faint objects, in the ultraviolet and in the infrared, could improve our knowledge on this fundamental parameter, which is one of the basic assumptions in the theories of thermonuclear runaway. An outburst can be reproduced by these theories if the mass of the white dwarf is larger than the average mass of single white dwarfs (about 0.6 solar masses). Now the existing data (Ritter catalogue, 1987) suggest that white dwarfs in nova systems are included between 0.6 and 1 solar masses, while dwarf novae and nova-like have both lower and higher values, ranging between 0.1 and 1.25 solar masses. However, the sample is much smaller for novae than for the two other groups. Is the frequency of fast and slow novae really different in our galaxy (fast novae represent more than 70% of all novae) and the Andromeda galaxy, where the slow novae are more abundant, according to Arp? Unfortunately we do not have ample statistics on the frequency of various types of novae in outer galaxies.

Another open question is: What are the physical differences that distinguish classical novae from recurrent novae? Some recurrent novae, like T CrB and RS Oph, have a red giant in the system, instead of a red dwarf. This could be a good reason for the difference. But we know that U Sco and T Pyx have a dwarf companion, just as classical novae.

Several novae have been observed in the X-ray range, with the satellites EINSTEIN and EXOSAT. They are rather weak sources in this spectral range. The average X-ray luminosity is about 6×10^{31} erg/s, while the average UV luminosity is 10^{34} – 10^{35} . There is some evidence (but based on a relatively small number of individuals) that fast novae are brighter X-ray sources than slow novae.

GK Per, during the minor outburst of August 9, 1983, was an exceptionally strong X-ray source in the range 2–20 keV, $L_x \sim 10^{34}$ erg s⁻¹.

This same nova was exceptional also in the radio range. Its spectrum indicates a non-thermal origin of the emission, in contrast to all the other classical novae. Interaction with an old planetary nebula in its surrounding could be the reason for this peculiarity.

Thermal radio emission from the envelopes of classical novae has been observed in few cases, and always later than 100 days from outburst for fast novae and as late as 1000 days for the very slow nova HR Del. Instead the recurrent nova RS Oph was found to be a non thermal radio source as soon as 18 days after its last outburst of 1985. A possible explanation could be the interaction of the expanding envelope with the previous ejecta. To this point, it is interesting to note that the recurrent nova T Pyx has an envelope presenting several shells, probably produced in different outbursts. This property is not shared by the envelopes of classical novae, which present polar or equatorial blobs with different chemical and physical properties, but not multiple shells.

II. THE THEORIES

Even though novae have been known and studied for a very long time, the subject is still extremely controversial. Many apparently complex phenomena are observed, and their interpretation is uncertain.

Before its outburst, a classical nova very much resembles a dwarf nova or "nova-like" binary. A component on or very near the lower main sequence in almost all cases appears to lose mass to a companion, usually via an accretion disk. The companion is most easily understood as being a white dwarf. Sudden brightening occurs, followed by a slower fading to a brightness nearly always close to that shortly before the outburst. Examination of the spectrum during an outburst shows spectral line profiles characteristic of a medium in expansion, different layers having different expansion velocities. The brightening can therefore be understood as due to expansion of an initially optically thick envelope, which is ejected at high velocities. The envelope becomes optically thinner with time and eventually has the properties of an expanding nebula, which can be studied in the radio and, even resolved spatially in very late stages. The nova remains active for a long time after the start of the outburst, its bolometric brightness declines very slowly, with most radiation being radiated at shorter and shorter wavelengths (ultraviolet and X rays) in later stages. This bolometric luminosity is not far from the Eddington limit; approximate calculations suggest that the total (radiative and kinetic energy) flux of FH Ser at least may have stayed for some time well above the Eddington limit.

Sometimes a large infrared excess is observed, interpreted as due to dust condensation. The dust appears to be sometimes optically thick, absorbing and reemitting radiation from the centre of the expanding envelope. Absorption by it can also affect emission line profiles. Overabundances in CNO and sometimes in heavier elements, which have been found particularly from studies of the nebular stage, appear to be real. The overabundances are probably related to the speed with which a nova undergoes its development during outburst. A clear anticorrelation between the O/H ratio and the time to decline 3 magnitudes (t_3) was found by Pacheco and Codina (1985).

However, many of the things that happen during an outburst are not clear. In the develop-

ment of an outburst, higher velocity material appears later and is almost certainly nearer the center of the envelope. It is hard to avoid the conclusion that continued ejection occurs, and the apparent absence of detectable low-velocity material near the centre of the envelope would appear to indicate that the wind is optically thick. The last conclusion is not always accepted, and one future aim must be to test this further. In any case, it is not easy to explain the presence of many layers, having different expansion velocities. A high-velocity wind would form a dense shell by a snowplow effect, following collision with slower moving material ejected at the beginning of an outburst, but usually more layers at different velocities are seen. Collisions between parts of the wind not ejected at the same time with different velocities are possible, while various instabilities may lead to the formation of cool clouds in the line of sight. The dynamics of such processes, including the formation of hot plasma, needs a lot of detailed study. It remains to be seen whether part of the physics is still missing from present ideas. Another point to be emphasized is that ejected material is not spherically symmetric, the origin of polar caps, equatorial rings, etc. is not understood.

Though nobody who works in the field now challenges the theory that the classical nova outbursts are due to thermonuclear runaways in the hydrogen accreted by the white dwarf component of the binary, many problems still remain. The great success of the theory was the prediction that a fast nova, i.e., a nova that undergoes its outburst development rapidly, must have CNO overabundances. The overabundances sometimes observed in heavier elements may be explainable if the outburst then occurs on a very massive white dwarf having a different composition. However, it is difficult to take account of the deviation from spherical symmetry in the accretion process of the white dwarf. In addition, complex processes can be expected during outburst in the general framework of the theory. The outer layers of the white dwarf should expand and engulf the companion star, the motion of the latter in the envelope should generate an extra luminosity, and the result might be a total luminosity

above the Eddington limit. In that case, the radiation pressure associated with the luminosity could accelerate an optically thick wind at large optical depth. Other problems also exist for the theory of nova outbursts. In particular, do novae “hibernate” during outbursts?

It is not clear how different recurrent novae are from classical novae. Recurrent novae do not form a homogeneous group, and it is to be hoped that the number of classes of recurrent novae does not become larger than five, the number of recurrent novae known at the time of this writing! Two (T CrB and RS Oph) have an orbital period of about 200 days, which is much longer than that of classical novae, while the stellar companion is a red giant. These recurrent novae show no clear sign of continued ejection.

The outburst spectrum of RS Oph shows the presence of both a low-velocity and a high-velocity component, the latter having a decreasing velocity with time. The spectral development, as well as the observed X-ray emission, have been successfully explained by the interaction of the envelope ejected at high velocity, and the low-velocity wind of the companion red-giant star into which it is ejected. A similar model may work for T CrB, but the three other recurrent novae are different; T Pyx, for instance, cannot have a red giant binary companion. As far as the outburst mechanism is concerned, the situation for recurrent novae is not at all clear. Thermonuclear events have been challenged in the cases of T CrB and RS Oph, for which accretion events have been proposed. However, at the time of this writing there is no consensus about this.

REFERENCES

- Adams, W.S., and Joy, A.H. 1933, *Pub. A.S.P.*, 45, 249.
- Ahnert, Von P. 1960, *Astr. Nach.*, 285, 191.
- Alcock, K.G. 1967, *Brit. Astron. Assoc. Circ.* 488.
- Allen, C.W. 1973, *Astrophysical Quantities*, London, Athlone Press.
- Aller, L.H. 1978, in "IAU Coll.no 76, Planetary Nebulae" ed. Y. Terzian, Dordrecht, Reidel p.225.
- Aller, L.H. 1984, "Physics of Thermal Gaseous Nebulae" (Dordrecht: Reidel).
- Altamore, A., Baratta, G.B., Cassatella, A., Friedjung, M., Giangrande, A., and Viotti, R.1981, *Ap.J.* 245, 630.
- Altunin, V. I.1976, *Soviet Astr. (Letters)*, 2, 116.
- Ambarzumian, V.A. 1932, *Pulkovo Circ.*, 4, .8.
- Ambarzumian, V.A. and Kosirev, N. 1933, *Z.f. Ap.* 7, 320.
- Ambruster, C.W., Blitzstein, W, Hull, A.B., and Koch, R.H. 1977, *Soviet. Astr.*, 21, 336.
- Anderson, P.H., Borra, E.F., and Dubas O.V. 1971, *Pub. A.S.P.*, 83, 5.
- Anderson, C.M., Gallagher, J.S. 1977, *Pub. A.S.P.*, 89,264.
- Andrillat, Y., and Fehrenbach, C. 1981, *Ap. Space Sci*, 76, 149.
- Andrillat, Y., Fehrenbach, C., and Houziaux, L. 1974, *Ap. Space Sci.*, 31, 169.
- Andrillat, Y., Friedjung, G.M.,and Puget, P. 1982, *Proceed. of 3rd European IUE Confer.* ESA SP 176, p.191.
- Andrillat, Y., and Houziaux, L. 1970a, *Ap. Space Sci*, 6, 36.
- Andrillat, Y., and Houziaux, L. 1970b, *Ap. Space Sci*, 9, 410.
- Andrillat, Y., and Houziaux, L. 1971, *Ap. Space Sci.*, 13, 100.
- Antipova, L.I. 1971, *Astr. Zh.*, 48, 288.
- Antipova, L.I. 1974, *Highlights of Astronomy*, 3., ed. G. Contopoulos, (Dordrecht: Reidel), p. 501.
- Antipova, L.I. 1977, *Astr. Zh.*, 54, 68 = *Soviet Astr.*, 21, 38.
- Arp, H.C. 1956, *A.J.*, 61, 15.
- Baade, W. 1947, *Pub. A.S.P.*, 53, 319.
- Baade, W., and Zwicky, F. 1934, *Proc. Nat. Acad. Sci.*, 20, 259.
- Barlow, M.J., Brodie, J.P., Brunt, C.C., Hanes, D.A., Hill, P.W., Mayo, S.K., Pringle, J.E., Ward, M.J., Watson, M.G., Whelan, J.A.J., and Willis, A.J. 1981, *M.N.R.A.S.*, 195, 61.
- Barnard, E.E. 1919, *Ap.J.*, 49, 199.
- Bartl, E., and Szumiejko, E. 1975, *Acta Astr.*, 25, 265.
- Bath, G.T. 1973, *Nature Phys. Sci.*, 246, 84.
- Bath, G.T. 1978, *M.N.R.A.S.*, 182, 35.
- Bath, G.T., and Pringle, J.E. 1981, *M.N.R.A.S.*, 194, 964.
- Bath, G.T., and Shaviv, G. 1976, *M.N.R.A.S.*, 175, 305.
- Bath, G.T., and Shaviv, G. 1978, *M.N.R.A.S.*, 183, 515.
- Bayley, J., Hyland, A.R., and Hillier, M. 1985, *A.A.O.*, 34.
- Beals, C.S. 1932, *M.N.R.A.S.*, 92, 677.
- Beardsley, W.B., King, M.W., Russell, J.L., and Stein, J.W. 1975, *Pub. A.S.P.*, 87, 943.
- Becker, R.H. 1981, *Ap. J.*, 251, 626.
- Becker, H.J., and Duerbeck, H.W. 1980, *Pub. A.S.P.*, 92, 792.
- Becker, R.H., and Marshall, F.E. 1981, *Ap. J. (Letters)*, 244, L93.
- Beer, A. 1935, *M.N.R.A.S.*, 93, 538.
- Beer, A. 1936, *M.N.R.A.S.*, 96, 238.
- Beer, A. 1974, *Vistas in Astr.*, 16, 179.
- Bertsch, D.L., Fichtel, C.E., Reames, D.V. 1972, *Ap.J.* 171, 169.
- Bianchini, A. 1980, *M.N.R.A.S.*,192, 127.
- Bianchini, A. 1988, *IBVS*, No. 3136.
- Bianchini, A., Friedjung, M., and Brinkmann, W. 1988, in preparation.
- Bianchini, A., Friedjung, M., and Sabbadin, F. 1985a, *Inf. Bull. Var. Stars*, No. 2650.
- Bianchini, A., Friedjung, M., and Sabbadin, F. 1985b, in *Recent Results on Cataclysmic Variables*, ed. W. Burke, ESA SP-236, 77.
- Bianchini, A., Hamzaoglu, E., and Sabbadin, F. 1981, *Astr. Ap.*, 99, 392.
- Bianchini, A., and Middelich, J. 1976, *IBVS*

- 1151.
- Bianchini, A., and Sabbadin, F. 1982, *ESA SP-176*, p.187.
- Bianchini, A., and Sabbadin, F. 1983, *Astr. Ap.*, 125, 112.
- Bianchini, A., and Sabbadin, F. 1985, *Inf. Bull. Var. Stars.*, No. 2751.
- Bianchini, A., and Sabbadin, F. 1987, in *HE - UHE Behaviour of Accreting X-Ray Sources*, Vulcano Workshop 1986, eds. F. Giovanelli and G. Mannocchi, (Bologna: Soc. It. di Fis.), p.53.
- Bianchini, A., Sabbadin, F., Favero, G.C., and Dalmeri, I. 1986, *Astr. Ap.*, 160, 367.
- Bianchini, A., Sabbadin, F., and Hamzaoglu, E. 1982, *Astr. Ap.* 106, 176.
- Biermann, L., 1939, *Z. Astrophys.*, 18, 344.
- Blair, W.P., Stencel, R.E., Feibelman, W.A., and Michalitsianos, A.G. 1983, *Ap.J.Suppl.* 53, 573.
- Blazit, A., Bonneau, D., Koechlin, L., and Labeyrie, A. 1977, *Ap. J. (Letters)*, 214, L79.
- Bloch, M., Dufay, J., Fehrenbach, Ch., and Tchong, M.L. 1946, *Ann.Ap.* 9,156.
- Bode, M.F.(editor) 1987, in *RS Ophiuchi (1985) and the Recurrent Nova Phenomenon*, (Utrecht:VNU Science Press).
- Bode, M.F., Duerbeck, H.D., Seitter, W.C., Albison, S., and Evans, A., 1988, *ESA SP-281*, vol. 1, 183.
- Bode, M.F., and Evans, A. 1981, *M.N.R.A.S.*, 197, 1055.
- Bode, M.F., and Evans, A. 1983, *Q.J. R.A.S.*, 24, 83.
- Bode, M.F., and Evans, A. 1985, *Astr. Ap.*, 151, 452.
- Bode, M.F., Evans, A., Whittet, D.C.B., Aitken, D.K., Roche, P.F., and Whitmore, B. 1984, *M.N.R.A.S.*, 207, 897.
- Bode, M.F., and Kahn, F.D. 1985, *M.N.R.A.S.*, 217, 205.
- Bode, M.F., Seaquist, E.R., and Evans, A. 1987a, *M.N.R.A.S.*, 228, 217.
- Bode, M.F., Seaquist, E.R., Frail, D.A., Roberts, J.A., Whittet, D.C.B., Evans, A., and Albison, J.S. 1987b, *Nature*, 329, 519.
- Bogges, A., Bohlin, R.C., Evans, D.C., Freeman, H.R., Gull, T.R., Heap, S.R., Klingle-Smith, D.A., Longanecker, G.R., Sparks, W., West, D.K., Holm, A.V., Perry, P.M., Schiffer III, F.H., Turnrose, B.E., Wu, C.C., Lane, A.L., Linsky, J.L., Savage, B.D., Benvenuti, P., Cassatella, A., Clavel, J., Heck, A., Macchetto, F., Penston, M.V., Selvelli, P.L., Dunford, E., Gondhalekar, P., Oliver, M.B., Sanford, M.C.W., Stickland, D., Boksenberg, A., Coleman, C.I., Snijders, M.A.J., and Wilson, R. 1978, *Nature*, 275, 377.
- Boyarchuk, A.A., Galkina, T.S., Gershberg, R.E., Krasnobabtsev, V.I., Rachkovshaya, T.I., and Shakhovskaya, N.S. 1977, *Soviet Astr.*, 21., 257.
- Bruch, A. 1980, *IBVS*, No. 1805.
- Bruch, A. 1982, *Pub. A.S.P.*, 94, 916.
- Bruch, A., Duerbeck, H.W., and Seitter, W.G. 1981, *Astr. Gesell. Mitt.* 52, 34.
- Burkhead, M.S., Penhallow, W.S., and Honeycutt, R.K. 1971, *Pub. A.S.P.*, 83, 338.
- Bychkova, V.S. 1982, *Astrofiz. Issl. -Izv. Spets. Astrofiz. Obs.*, 15, 3.
- Bychova, V.S., and Bychkov, K.V. 1976, *Astr. Zh.*, 53, 1196. = *Sov. Astr.*, 20, 675.
- Callus, C.M., Albison, J.S., Evans, A., and Bode, M.F. 1986, *Light on Dark Matter*, ed. F.P. Israel (Dordrecht: Reidel), p. 149.
- Campbell, B. 1975, *IAU Circ.*, No. 2839.
- Campbell, B. 1976, *Ap. J. (Letters)*, 207, L41.
- Campbell, L. 1919, *Harv. Ann.*, 81, 113.
- Campbell, L. 1929, *Harvard Bull.*, 835.
- Campbell, W.W. 1892, *Astr. Ap.*, 11. 799 (previously *The Sidereal Messenger*).
- Campolongo, F., Gilmozzi, R., Guidoni, U., Messi, R., Natali, G., and Wells, J. 1980, *Astr. Ap.*, 85, L4.
- Cannizzo, J.K., Ghosh, P., and Wheeler, J.C. 1982, *Ap. J. (Letters)*, 260, L83.
- Cannizzo, J.K., and Kenyon, S.J. 1986, *Ap. J. (Letters)*, 309, L43.
- Cannizzo, J.K., Wheeler, J.C., and Polidan P.S. 1986, *Ap. J.*, 301, 634.
- Cannon, A.J. 1920, *Harv. Ann.*, 81, 179.
- Carone, T.E., Polidan, R.S., and Wade, R.A., 1985, *Proc. of the Ninth North American Workshop on CV'S*, ed. P. Szkody (Depart. of Astron. Univ. of Washington), p. 11.

- Cassatella, A., Benvenuti, P., Clavel, J., Heck, A., Penston, M., Selvelli, P.L., and Macchetto, F. 1979, *Astr. Ap.*, 74, L18.
- Cassatella, A., Gilmozzi, R., and Selvelli, P.L. 1986, "New Insight in Astrophysics", (ESA-SP 263), p. 277.
- Cassatella, A., Gilmozzi, R. and Selvelli, P.L. 1990, in prep.
- Cassatella, A., and Gonzales Riestra, R. 1988, *Physics of Formation of FeII lines outside LTE*, eds. R.Viotti et al. (Dordrecht, Reidel), p. 115.
- Cassatella, A., Hassal, B.J.M., Harris, A., and Snijders, M.A.J. 1985, *Proc. ESA Workshop, Recent Results on Cataclysmic Variables*, (Bamberg, ESA SP-236), p. 281.
- Cassatella, A., Patriarchi, P., Selvelli, P.L., Bianchi, L., Cacciari, C., Heck, A., Perryman, M., and Wamsteker, W. 1982, *Proc. of Third Europ. Conf. (ESA-SP 176)*, p. 229.
- Castor, J.I., and Lamers, H.J.G.L.M. 1979, *Ap. J. Suppl.*, 39, 481.
- Catchpole, R.M. 1969, *M.N.R.A.S.*, 142, 119.
- Chandrasekhar, S. 1934, *M.N.R.A.S.*, 94, 444.
- Chevalier, R.A. 1977, *Astr. Ap.*, 59, 289.
- Chevalier, R.A. 1982, *Ap. J.*, 259, 302.
- Chevalier, R.A., and Klein, R.I. 1978, *Ap. J.*, 219, 994.
- Christy, R.F. 1966, *Ap. J.*, 144, 108.
- Chugaj, N.N. 1975, *Astr. Zh.*, 52, 197. = *Sov. Astr.*, 19, 119.
- Ciardullo, R., Ford, H., and Jacoby, G. 1983, *Ap. J.*, 272, 92.
- Ciatti, F., and Mammano, A. 1972, *Atti Acad. Naz. Lincei Ser.*, 8, 52 Fasc. 1, 62.
- Clayton, D.D., and Wickramasinghe, N.C. 1976, *Ap. Space Sci.*, 42, 463.
- Code, A.D. 1971, *The Scientific Results from OAO-2 (NASA SP-310)*, p.535.
- Cohen, J.G. 1985, *Ap. J.*, 292, 90.
- Cohen, J.G., and Rosenthal, A.J. 1983, *Ap. J.*, 268, 689.
- Collin-Souffrin, S. 1977, in "Novae and Related Stars", ed. M. Friedjung, (Dordrecht: Reidel), p.123.
- Collins, P.L. 1978, *IAU Circ.*, No. 3263.
- Colvin, J.D., Van Horn, H.M., Starrfield, S.G. and Truran, J.W. 1977, *Ap. J.* 212, 791.
- Cook, M.C. 1981, *M.N.R.A.S.*, 195, 51P.
- Cordova, F.A., Jensen, K.A., and Nugent, J.J. 1981a, *M.N.R.A.S.*, 196, 1.
- Cordova, F.A., and Mason, K.O. 1982, *Ap. J.*, 260, 716.
- Cordova, F.A., and Mason, K.O. 1984, *M.N.R.A.S.*, 206, 879.
- Cordova, F.A., and Mason, K.O. 1985, *Ap. J.*, 290, 671.
- Cordova, F.A., Mason, K.O., and Nelson, J.E. 1981b, *Ap. J.*, 245, 609.
- Couderc, P. 1939, *Phys. Ber. Leipzig*, 20, 2177.
- Crampton, D., Cowley, A.P., and Fisher, W.A. 1986, *Ap. J.*, 300, 788.
- Crampton, D., Cowley, A.P., and Hutchings, J.B. 1983, *IAU Colloquium 72, Cataclysmic Variables and Related Objects*, eds. M. Livio and G. Shaviv (Dordrecht, Reidel), p. 25.
- Davis, R.J. 1987, in *RS Ophiuchi (1985) and the Recurrent Nova Phenomenon*, ed. M.F. Bode (Utrecht: VNU Science Press).
- Delbourgo-Salvador, P., Mochkovitch, R., and Vangioni-Flam, E. 1985, *ESA SP-236*, p. 229.
- Dinerstein, H.L. 1986, *Astr. J.*, 92, 1381.
- Dmitrienko, E.S., and Cherepashchuk, A.M. 1980, *Soviet Astr.*, 24, 432.
- Doroshenko, V.T. 1968, *Soviet Astr.*, 12, 95.
- Drechsel, H., Rahe, J., Duerbeck, H.W., Kohoutek, L., and Seitter, W.C. 1977, *Astr. Ap. Suppl.*, 30, 323.
- Drechsel, H., Rahe, J., Holm, A., and Krautter, J. 1980, *The Messenger* No 22, p. 10.
- Drechsel, H., Rahe, J., Holm, A., and Krautter, J. 1981, *Astr. Ap.*, 99, 166.
- Drechsel, H., Rahe, J., Seward, F.D., Wang, Z.R., and Wargau, W. 1983a, *Astr. Ap.*, 126, 357.
- Drechsel, H., Rahe, J., and Wargau, W. 1983b, *The Messenger*, 32, p. 35.
- Drechsel, H., Wargau, W., Rahe, J. 1984, *Astr. Space Science* 99, 85.
- Duerbeck, H.W. 1980, *Habilitation thesis, Bonn University*.
- Duerbeck, H.W. 1981, *Pub. A.S.P.*, 93, 165.
- Duerbeck, H.W. 1984, *Astroph. Space Science*, 99, 363.

- Duerbeck, H.W. 1986, *Mitt. Astron. Ges.*, 67, 309.
- Duerbeck, H.W. 1987a, *Ap Space Sci*, 131, 461.
- Duerbeck, H.W. 1987b, *ESO Messenger*, 50, 8.
- Duerbeck, H.W. 1987c, *Space Sci. Rev.*, 45, 1.
- Duerbeck, H.W., Klare, G., Krautter, J., Wolf, B., Seitter, W.C., and Wargan, W. 1980a, *Proced. 2 IUE Conf. ESA S.P.*, 157, p. 91.
- Duerbeck, H.W., Rindermann, K., and Seitter, W.C. 1980b, *Astr. Ap.* 81, 157.
- Duerbeck, H.W., and Seitter, W.C. 1979, *ESO Messenger*, 17, 1.
- Duerbeck, H.W., and Seitter, W.C. 1980, *IBVS*.
- Duerbeck, H.W., and Seitter, W.C. 1987, *Ap. Space Sci*, 131, 467.
- Duerbeck, H.W., Seitter, W.C., and Duemmler, R. 1987, *M.N.R.A.S.*, 229, 653.
- Duerbeck, H.W., and Wolf, B. 1977, *Astr. Ap. Suppl.*, 29, 297.
- Dufay, J., and Bloch, M. 1964, *Ann. Ap.*, 27, 462.
- Dufay, J., Bloch, M., Bertaud, Ch., and Dufay, M. 1964, *Ann. Ap.*, 27, 555.
- Dultzin-Hacyan, D., Andrillat, Y., Audouze, J., Friedjung, M., Gordon, C., Rocca-Volmerange, B., and Stasinska, G. 1980, *Proceed. of 2nd Europ. IUE Cong.*, (ESA SP-157), p. 87.
- Duschl, W.J., Meyer-Hofmeister, E., and Meyer, F. 1985, in *Recent Results on Cataclysmic Variables*, ESA SP-236, 221.
- Eddington, A.S. 1921, *Zs. Physik*, 7, 351.
- Edward, D.A., and Pringle J.E., 1987, *M.N.R.A.S.* 229, 383.
- EGgen, O.J., Matheson, D.S., and Serkowski, K. 1967, *Nature*, 213, 216.
- Elvey, C.T., and Babcock, H.W. 1943, *Ap. J.*, 97, 412.
- Ennis, D., Becklin, E.E., Beckwith, S., Elias, J., Gatley, I., Matthews, K., Neugebauer, G., and Willner, S.P. 1977, *Ap. J.* 214, 478.
- Evans, A. 1985, *Observatory*, 105, 6.
- Evans, A. 1987, in *RS Ophiuchi (1985) and the Recurrent Nova Phenomenon*, ed. M.F. Bode, (Utrecht: VNU Science Press).
- Faulkner, J., Lin, D.N.C., and Papaloizou, J. 1983, *M.N.R.A.S.*, 205, 359.
- Feast, M.W., and Glass, I.S. 1974, *M.N.R.A.S.*, 167, 81.
- Fehrenbach, Ch., Andrillat, Y., and Bloch, M. 1967, *Publ. Obs. Haute Provence*, 9, No. 19.
- Fehrenbach, Ch., Andrillat, Y., and Bloch, M. 1968a, *Publ. Obs. Haute Provence*, 9, No. 25.
- Fehrenbach, Ch., Andrillat, Y., Bloch, M. and Houziaux, L. 1968b, *Publ. Obs. Haute Provence*, 10, No. 7.
- Fehrenbach, Ch., and Petit, M. 1969, *Astr. Ap.*, 1, 403.
- Ferland, G.J. 1977a, *Ap. J. (Letters)*, 212, L21.
- Ferland, G.J. 1977b, *Ap. J.*, 215, 873.
- Ferland, G.J. 1980, *Observatory*, 100, 166.
- Ferland, G.J., Lambert, D.L., Netser, H., Hall, D.N.B., Ridgeway, S.T. 1979, *Ap. J.* 227, 489.
- Ferland, G.J., Lambert, D.L., McCall, M.L., Shields, G.A., and Slovak, M.H. 1982 a, *Ap. J.*, 260, 794.
- Ferland, G.J., Lambert, D.L., Netzer, H., Hall, D.N.B., and Ridgeway, S.T. 1979, *Ap. J.* 227, 489.
- Ferland, G.J., Lambert, D.L., and Woodman, J.H. 1977, *Ap. J.*, 213, 132.
- Ferland, G.J., Lambert, D.L., and Woodman, J.H. 1986, *Ap. J. Suppl.*, 60, 375.
- Ferland, G.J., Longer, S.H., Mac Donald, J., Pepper, G.H., Shaviv, G., and Truran, J.W. 1982b, *Ap. J.*, 262, L53.
- Ferland, G.J., and Shields, G.A., 1978a, *Ap. J. (Letters)*, 224, L15.
- Ferland, G.J., and Shields, G.A. 1978b, *Ap. J.*, 226, 172.
- Ferland, G.J., and Truran, J.W. 1981, *Ap. J.*, 244, 1022.
- Ferland, G.J., Williams, R.E., Lambert, D.L., Shields, G.A., Slovak, M., Gondhalekar, P.M., and Truran, J.W. 1984, *Ap. J.*, 281, 194.
- Fiedler, R.L., and Jones, T.W. 1980, *Ap. J.*, 239, 253.
- Finzi, A. 1973, *Ap. J.*, 183, 183.
- Folkart, B., Pecker, J.C., and Pottasch, S.R. 1964, *Ann. Ap.*, 27, 249.
- Folkart, B., Pecker, J.C., and Pottasch, S.R. 1964, *Ann. Ap.*, 27, 252.
- Fried, J.W. 1980, *Astr. Ap.*, 81, 182.
- Friedjung, M. 1966a, *M.N.R.A.S.*, 131, 447.
- Friedjung, M. 1966b, *M.N.R.A.S.*, 132, 143.
- Friedjung, M. 1966c, *M.N.R.A.S.*, 132, 317.
- Friedjung, M. 1968, *Astroph. Lett.* 2, 121.

- Friedjung, M. 1977a, *Novae and Related Stars*, ed. M. Friedjung. (Dordrecht, Netherlands), p. 61.
- Friedjung, M. 1977b, in *Novae and Related Stars*, ed. M. Friedjung, (Dordrecht: Reidel), p. 95.
- Friedjung, M. 1981a, *Acta Astr.*, 31, 373.
- Friedjung, M. 1981b, *Astr. Ap.*, 93, 320.
- Friedjung, M. 1985, in *Multifrequency Behavior of Galactic Accreting Sources*, ed. F. Giovanelli, (CSN: Frascati), p. 65.
- Friedjung, M. 1987a, *Astr. Ap.*, 180, 155.
- Friedjung, M. 1987b, *Astr. Ap.*, 179, 164.
- Friedjung, M. 1988, *Classical Novae*, eds. M.F. Bode and A. Evans, (Wiley Interscience).
- Friedjung, M., Andrillat, Y, and Puget, P. 1982, *Astr. Ap.*, 114, 351.
- Friedjung, M., and Smith, M.G. 1966, *M.N.R.A.S.*, 132, 239.
- Fujimoto, M.Y. 1982, *Ap. J.*, 257, 752 and 767.
- Galeotti, P., and Pasinetti, L.E. 1970, *Contr. Oss. Astr. Milano-Merate N.S.*, Nos. 328, 329.
- Gallagher, J.S. 1977, *Astr. J.*, 82, 209.
- Gallagher, J.S. and Code, A.D. 1974, *Ap. J.*, 189, 303.
- Gallagher, J.S., Hege, E.K., Kopriva, D.A., Williams, R.E., and Butcher, H.R. 1980, *Ap. J.*, 237, 55.
- Gallagher, J.S., and Holm, A.V. 1974, *Ap. J.*, 189, L123..
- Gallagher, J.S., and Ney, E.P. 1976, *Ap. J. (Letters)*, 204, L35.
- Gallagher, J.S., and Oinas, V. 1974, *Pub. A.S.P.*, 86, 952.
- Gallagher, J.S., and Starrfield, S. 1976, *M.N.R.A.S.*, 176, 53.
- Gallagher, J.S., and Starrfield, S. 1978, *Ann. Rev. Astr. Ap.*, 16, 171.
- Gehrz, R.D., Grasdalen, G.L., Hackwell, J.A., and Ney, E.P. 1978, *IAU Circ.* 3296.
- Gehrz, R.D., Grasdalen, G.L., Hackwell, J.A., and Ney, E.P. 1980a *Ap. J.*, 237, 855.
- Gehrz, R.D., Grasdalen, G.L., and Hackwell, J.A. 1985, *Ap. J. (Letters)*, 298, L47.
- Gehrz, R.D., Grasdalen, G.L., Greenhouse, M., Hackwell, J.A., Hayward, T., and Bentley, A.F. 1986, *Ap. J. (Letters)*, 308, L63.
- Gehrz, R.D., Hackwell, J.A., Grasdalen, G.L., Ney, E.P., Neugebauer, G., and Sellgren, K. 1980b, *Ap. J.*, 239, 570.
- Geisel, S.L., Kleinmann, D.E., and Low, F.J. 1970, *Ap. J. (Letters)*, 161, L101.
- Gershberg, R.E. 1964, *Izv. Krym. Astrofiz.*, 32, 133.
- Giacconi, R., Branduardi, G., Briel, U., Epstein, A., Fabricant, D., Feigelson, E., Forman, W., Gorenstein, P., Grindlay, J., Gursky, H., Harnder, Jr., F.R., Henry, J.P., Jones, C., Kellogg, E., Koch, D., Murray, S., Schreier, E., Seward, F., Tananbaum, H., Topka, K., Van Speybroek, L., Holt, S.S., Becker, R.H., Boldt, E.A., Serlemitsos, P.J., Clark, G., Canizares, C., Markert, T., Novick, R., Helfand, D, and Long, K. 1979, *Ap. J.*, 230, 540.
- Giannone, P., and Weigert, A. 1967, *Zs. Astrophys.*, 67, 41.
- Gilliland, R.L., Kemper, E., and Suntzeff, N. 1986, *Ap. J.*, 301, 252.
- Gilmozzi, R., Cassatella, A. and Selvelli, P.L. 1987, in *Proc. of Vulcano Workshop 1986, He-UHE Behaviour of Accreting X-Ray Sources*, eds. F. Giovanelli and G. Mannocchi, (Italian Physical Society Conference Proceedings), Vol. 8, p. 49.
- Giuricin, G., Mardirossian, F., Mezzetti, M., Pucillo, M., Santin, P., and Sedmak, G. 1979, *Astr. Ap.*, 80, 9.
- Gorbatskii, V.G. 1958, *Scientific Notes of the Leningrad State Univ.*, No. 273, Math. Section, No. 34, p. 30.
- Gorbatskii, V.G. 1962, *Scientific Notes of the Leningrad State Univ.*, No. 307, Math. Section, No. 36, p. 45.
- Gorbatskii, V.G. 1972, *Astr. Zh.*, 49, 42. = *Sov. Astr.*, 16, 32.
- Gorbatskii, V.G. 1973, *Astr. Zh.*, 50, 19. = *Sov. Astr.*, 17, 11.
- Gorbatskii, V.G. 1974, *Astrophysic*, 8, 220.
- Gorbatskii, V.G. 1977 *Astr. Zh.* 54, 1036; *Sov. Astr.* 21, 587.
- Gorbatskii, V.G., and Minin, I.N. 1963, in *Non Stable Stars*, (Moscow: State Pub. House), p. 355.
- Gordeladse, Sh.G. 1937, *Byull. Abastumani Astrofiz. Obs.*, 1, 55.
- Greenstein, J.L. 1960, *Stellar Atmospheres*, ed. J.L. Greenstein, (Univ. of Chicago), p. 676.
- Greenstein, J.L., and Kraft, R.P. 1959, *Ap. J.*,

- 130, 99.
- Grotrian, W. 1930, *Zs. Astrophys.*, 2, 78.
- Grotrian, W. 1937, *Zs. Astrophys.*, 13, 215.
- Gurevich, L.E., and Lebedinskii, A.I. 1947a, *Doklady AN SSSR* 56, No. 1, 2.
- Gurevich, L.E., and Lebedinskii, A.I. 1947b, *Zhurn. Eksperim. i Teor. Fiz.*, 17, 792.
- Gyldenkerne, K., Meydahl, V., and West, R.M. 1969, *Pub. Mindre Medd. Kobenhavns Obs.*, No. 201.
- Haefner, R. 1981, *IBVS*, No. 2045.
- Haefner, R., and Metz, K. 1982, *Astr. Ap.*, 109, 171.
- Haefner, R., and Metz, K. 1985, *Astr. Ap.*, 145, 311.
- Haefner, R., and Schoembs, R. 1985, *Astr. Ap.*, 150, 325.
- Halm, J. 1901, *Astr. Nachr.*, 156, 147.
- Halm, J. 1904, *Proc. Roy. Soc. Edinburgh*, 25, 513.
- Hanes, D.A. 1985, *M.N.R.A.S.*, 213, 443.
- Hanuschik, R.W., and Dachs, J. 1987, in *ESO Workshop on the SN 1987 A*, ed. I.J. Danziger, p. 153.
- Harkness, R.P. 1983, *M.N.R.A.S.*, 204, 45.
- Hartmann, J. 1925, *Astr. Nachr.*, 226, 63.
- Hartmann, J. 1926, *Astr. Nachr.*, 226, 203.
- Hazlehurst, J. 1962, *Advances in Astr. Ap.*, 2, ed. Z. Kopal, (New York and London: Academic Press), p. 1.
- Henbest, N. 1987, *New Scientist* 116, No. 1585, p. 52.
- Herbig, G. 1955, (see Beer 1974) in *Vistas*, 16, 179, p. 259.
- Herbig, G.H., and Neubauer F.J. 1946, *Pub. A.S.P.*, 58, 196.
- Herczeg, T. 1982, *IBVS*, No. 2078.
- Hjellming, R.M., van Gorkom, J.H., Taylor, A.R., Seaquist, E.R., Padin, S., Davis, R.J., and Bode, M.F. 1986, *Ap. J. (Letters)*, 305, L71.
- Hjellming, R.M., and Wade, C.M. 1970, *Ap. J. (Letters)*, 162, L1.
- Hjellming, R.M., Wade, C.M., Vandenberg, N.R., and Newell, E.B. 1979, *Astron. J.*, 84, 1619.
- Hoffmann, J.A., Lewin, W.H.G., Brecher, K. Buff, J., Clark, G.W., Joss, P.C., and Matilsky, T. 1976, *Nature* 261, 208.
- Holm, A., and Crabb, W. 1979, *NASA IUE (Letter 7)*, p. 40.
- Honda, M. 1982, *IAU Circ. No.* 3661.
- Hoshi, R. 1979, *Prog. Theor. Phys.*, 61, 1307.
- Huang, S.S. 1956, *Astron. J.* 61, 49.
- Hudec, R. 1978, *Bull. Astr. Inst. Czech.*, 32, 93.
- Huggins, W., 1892, *Astr. Ap.*, 11, 571.
- Huggins, W., and Miller, W.A. 1866, *Proc. Roy. Soc. London* 15, 146. - *M.N.R.A.S.*, 26, 275.
- Humason, M.L. 1938, *Ap. J.*, 88, 228.
- Hutchings, J.B. 1969, *Pub. Dom. Ap. Obs.*, 13, 14 and 16.
- Hutchings, J.B. 1972, *M.N.R.A.S.*, 158, 177.
- Hutchings, J.B. 1979a, *Pub. A.S.P.*, 91, 661.
- Hutchings, J.B. 1979b, *Ap. J.*, 230, 162.
- Hutchings, J.B. 1980, *Pub. A.S.P.*, 92, 458.
- Hutchings, J.B., and Fisher, W.A. 1973, *Pub. A.S.P.*, 85, 122.
- Hutchings, J.B., Smolinski, J., and Grygar, J. 1971, *Pub. A.S.P.*, 83, 15.
- Hyland, A.R., and Neugebauer, G. 1970, *Ap. J. (Letters)* 160, L177.
- Iben, Jr., I., and Tutukov, A.V. 1984, *Ap. J. Suppl.*, 54, 335.
- Iwanoska, W., Mitchell, W.E., and Keenan, P.C. 1960, *Ap. J.*, 132, 271.
- Jenkins, E.B., Snow, T.P., Upson, W.L., Starrfield, S.G., Gallagher, J.S., Friedjung, M., Linsky, J.L., Anderson, R., Henry, R.C., and Moos, H.W., *Ap. J.* 1977, 212, 198.
- Jensen, K.A. 1984, *Ap. J.* 278, 278.
- Jensen, K.A. 1985, *Cataclysmic Variables and Low Mass X-Ray Binaries*, eds. D.Q. Lamb and J. Patterson (Dordrecht: Reidel), p. 407.
- Joy, A.H., 1938, *Pub. A.S.P.*, 50, 300.
- Joy, A.H., 1945, *Pub. A.S.P.*, 57, 171.
- Joy, A.H., and Swings, P. 1945, *Ap. J.*, 102, 353.
- Kahn, F.D. 1976, *Astr. Ap.*, 50, 145.
- Kaler, J.B. 1986, *Pub. A.S.P.*, 98, 243.
- Kaplan, S.A., and Pikelner, S.B. 1970, *The Interstellar Medium*, (Cambridge: Cambridge Univ. Press.), p. 19.
- Kato, M. 1983, *Publ. Astron. Soc. Japan* 39, 507.
- Kato, M., and Hachisu, I. 1988 *Ap. J.* 329, 808.

- Kenyon S.J. 1986, *Astr. J.*, 91, 503.
- Kenyon, S.J. 1988, in *IAU Colloquium 103, The Symbiotic Phenomenon*, eds. J. Mikolajewska, M. Friedjung, S.J. Kenyon and R. Viotti, (Kluwer Academic Publish.), p. 161.
- Kenyon, S.J., and Berriman, G. 1988, *Astr. J.*, 95, 526.
- Kenyon, S.J., and Garcia, M.R. 1986, *Astr. J.*, 91, 125.
- Kenyon, S.J., and Webbink, R.F. 1984, *Ap. J.* 279, 252.
- King, A.R., Ricketts, M.J., and Warwick, R.S. 1979, *M.N.R.A.S.*, 187, 77P.
- Kippenhahn R., and Thomas, H.C. 1978, *Astr. Ap.* 63, 265.
- Klare, G., Wolf, B., and Krautter, J. 1980, *Astr. Ap.*, 89, 282.
- Kleine, T., and Kohoutek, L. 1979, *Astr. Ap.*, 76, 133.
- Kohoutek, L. 1981, *M.N.R.A.S.*, 196, 87p.
- Kohoutek, L., and Pauls, R. 1980, *Astr. Ap.*, 92, 200.
- Kolotilov, E.A., 1980, *Soviet Astr. (Letters)*, 6, 268.
- Kopal, Z. 1987, Private Communication to Seitter in *RS Ophiuchi (1985) and the Recurrent Nova Phenomenon*, ed. M.F. Bode, (Utrecht: VNU Science Press), p. 63.
- Kosirev, N.A. 1934, *M.N.R.A.S.*, 94, 430.
- Kraft, R.P. 1958, *Ap. J.*, 127, 625.
- Kraft, R.P. 1959, *Ap. J.*, 130, 110.
- Kraft, R.P. 1963, *Advances in Astronomy and Astrophysics 2*, ed. Z. Kopal, (New York and London: Academic Press), p. 43.
- Kraft, R.P. 1964, *Ap. J.*, 139, 457.
- Krautter, J. 1986, *Proceedings IUE Conference: New Insights in Astrophysics*, (ESA SP-263), p. 275.
- Krautter, J., Beuermann, K., Leitherer, C., Oliva, E., Moorwood, A.F.M., Deul, E., Wargau, W., Klare, G., Kohoutek, L., Van Paradijs, J., and Wolf, B. 1984, *Astr. Ap.*, 137, 307.
- Krautter, J., Beuermann, K., and Ogelman, H. 1985, *Space Sci Rev.*, 40, 156.
- Krautter, J., Klaas, U., and Radons, G. 1987, *Astr. Ap.*, 181, 373.
- Krautter, J., Klare, G., Wolf, B., Duerbeck, H.W., Rahe, J., Vogt, N., and Wargau, W. 1981, *Astr. Ap.*, 102, 337.
- Kruszewski, A., Semeniuk, I., and Duerbeck, H.W. 1983, *Acta Astr.* 33, 339.
- Kubiak, M. 1984, *Acta Astr.*, 34, 331.
- Kupo, I., and Leibowitz, E.M. 1977, *Astr. Ap.*, 56, 181.
- Kurochkin, N.E., and Karitskaya, E.A. 1986, *Astr. Tsirk.*, No. 1441, 7.
- Kurucz, R.L. 1979, *Ap. J. Suppl.*, 40, P1.
- Kutter, G.S., and Sparks, W.M. 1987, in press.
- Kylafis, N.D., and Lamb, 1982, *Ap. J.*, 48, 239.
- Lacy, C.H. 1977, *Ap. J. Suppl.* 34, 479.
- Lambert, D.L. 1978, *M.N.R.A.S.* 182, 249.
- Lambert, D.L., Slovak, M.H., and Shields, G.A. 1980, *NASA Conf. Publ.* 2171, *The Universe at UV wavelengths*, (Greenbelt, Maryland), p. 461.
- Lance, C.M., McCall, M.L., and Uomoto, A.K. 1988, *Ap. J. Suppl.*, 66, 151.
- Lancy, D. 1985, *IAU Circ.*, No. 4036.
- Larsson-Leander, G. 1953, *Stockholm Ann.* 17, No. 8.
- Larsson-Leander, G. 1954, *Stockholm Ann.* 18, No. 4.
- Lau, H.E. 1906, *Bull. Astr.*, 23, 297.
- Law, W.Y., and Ritter, H. 1983, *Astr. Ap.*, 123, 33.
- Lebedinskii, A.I. 1946, *Astr. Zh.*, 23, 15.
- Lewin, W.H.G., Doty, J., Clark, G.W., Rappaport, S.A., Bradt, H.V.D., Doksey, R., Hearn, D.R., Hoffmann, J.A., Jernigan, J.G., Li, F.K., Mayer, W., McClintock, J., Primini, F., and Richardson, J. 1976, *Ap. J. (Letters)* 207, L95.
- Livio, M. 1987, *Comments Astrophys.*, 12, 87.
- Livio, M. 1988a, in *IAU Colloquium 103, The Symbiotic Phenomenon*, eds. J. Mikolajewska, M. Friedjung, S.J. Kenyon, R. Viotti, (Kluwer Academic Publ.), p. 323.
- Livio, M. 1988b, in *IAU Colloquium 108, Atmospheric Diagnostics of Stellar Evolution*, K. Nomoto, ed., p. 226.
- Livio, M., Truran, J.W., and Webbink, R. 1986, *Ap. J.*, 308, 736.
- Lockwood, G.W., and Millis, R.L. 1976, *Pub. A.S.P.*, 88, 235.
- Loreta, E. 1987, in *Rosino, RS Ophiuchi (1985)*

- and the Recurrent Nova Phenomenon, ed. M.F. Bode, (Utrecht: VNU Science Press), p. 4.
- Lynden-Bell, D. 1969, *Nature*, 223, 690.
- MacDonald, J. 1980, *M.N.R.A.S.*, 191, 933.
- MacDonald, J. 1983, *Ap. J.*, 273, 289.
- MacDonald, J. 1986, *Ap. J.*, 305, 251.
- MacDonald, J., Fujimoto, M.Y., and Truran, J.W. 1985, *Ap. J.*, 294, 263.
- Malakpur, I. 1973a, *Astr. Ap.*, 24, 125.
- Malakpur, I. 1973b, *Astr. Ap.*, 28, 393.
- Malakpur, I. 1973c, *Astroph. Space Sci.* 24, 577.
- Malakpur, I. 1980, *Ap. Space Sci.*, 72, 143.
- Marino, B.F., and Walker, M.F. 1982, *Publ. Var. Star Section, Roy. Astr. Soc. (New Zealand)*.
- Mason, K.O., Cordova, F.A., Bode, M.F., and Barr, P. 1987, *RS Ophiuchi (1985) and the Recurrent Nova Phenomenon*, ed. M.F. Bode, (Utrecht: VNU Science Press), p. 167.
- Mattei-Akyuz, J. 1974, *J.R.A.S. Canada*, 68, 22.
- Mazeh, T., Netzer, H., Shaviv, G., Drechsel, H., Rahe, J., Wargau, W., Blades, J.C., Cacciari, C., and Wamsteker, W. 1985 a, *Astr. Ap.*, 149, 83.
- Mazeh, T., Tal, Y., Shaviv, G., Bruch, A., and Budell, R. 1985b, *Astr. Ap.*, 149, 470.
- McCray, R. 1983, in *Highlights of Astronomy* 6, ed. R.M. West, p. 565.
- McCrea, W.H. 1937, *Observatory*, 60, 277.
- McKellar, A. 1937, *Publ. Dom. Ap. Obs.*, 6, 353.
- McLaughlin, D.B. 1935, *Publ. Am. Astron. Soc.*, 8, 145.
- McLaughlin, D.B. 1937, *Publ. Obs. Univ. Michigan*, 6, No. 12, 107.
- McLaughlin, D.B. 1942, *Ap. J.*, 95, 428.
- McLaughlin, D.B. 1943, *Publ. Obs. Univ. Michigan*, 8, No. 12, 149.
- McLaughlin, D.B. 1945, *Pub. A.S.P.*, 57, 69.
- McLaughlin, D.B. 1946, *Pub. A.S.P.*, 58, 46.
- McLaughlin, D.B. 1947, *Pub. A.S.P.*, 59, 244.
- McLaughlin, D.B. 1950, *Pub. A.S.P.*, 62, 185.
- McLaughlin, D.B. 1954, *Ap. J.*, 119, 124.
- McLaughlin, D.B. 1960, in *Stars and Stellar Systems VI*, ed. J.L. Greenstein, *Stellar Atmospheres*, (Chicago: Univ. of Chicago Press) p. 585.
- McLaughlin, D.B. 1969, *Pub. Obs. Univ. Michigan*, vol. IX, No. 3.
- Medway, K. 1985, *IAU Circ.*, No. 4048.
- Meinel, A.B. 1963, *Ap. J.*, 137, 834.
- Mendoza, C. 1983, in *IAU Symposium 103, Planetary Nebulae*, ed. D.R. Flower, (Dordrecht: Reidel), p. 143.
- Menzel, D.H., and Payne, C. 1933, *Wash. Nat. Acad. Proc.*, 19, 641.
- Mestel, L. 1952, *M.N.R.A.S.*, 112, 598.
- Meyer, F., and Meyer-Hofmeister, E. 1981, *Astr. Ap. (Letters)*, 104, L10.
- Meyer, F., and Meyer-Hofmeister, E. 1982, *Astr. Ap.*, 106, 34.
- Middleditch, J., and Nelson, J. 1979, *Bull. AAS*, 11, 664.
- Middleditch, J., and Nelson, J. 1980, *Bull. AAS*, 12, 848.
- Milne, E.A. 1926, *M.N.R.A.S.*, 86, 459.
- Milne, E.A. 1931, *M.N.R.A.S.*, 91, 4. - *Observatory*, 54, 140.
- Mineshige, S., and Osaki, Y. 1983, *Pub. Astr. Soc. Japan*, 35, 377.
- Mitchell, R.M., Evans, A., and Albinson, J.S. 1986, *M.N.R.A.S.* 221, 663.
- Mitchell, R.M., Robinson, G., Hyland, A.R., and Neugebauer, G. 1985, *M.N.R.A.S.*, 216, 1057.
- Morrison, W. 1985, *IAU Circ.*, No. 4030.
- Mumford, G.S. 1966a, *Ap. J.*, 146, 111.
- Mumford, G.S. 1966b, *Ap. J.*, 146, 962.
- Mumford, G.S. 1971, *Ap. J.*, 165, 369.
- Mustel, E.R. 1957, in *IAU Symposium 3, Non-Stable Stars*, ed. G.H. Herbig, (Cambridge: Univ. of Cambridge Press), p. 57.
- Mustel, E.R. 1956, *The mechanism of ejection of matter from novae*, *Vistas in Astr.*, ed. A. Beer, 2, p. 1496.
- Mustel, E.R. 1958, in *IAU Symposium 6, Electromagnetic Phenomena in Cosmical Physics*, ed. B. Lehnert, London, Cambridge Univ. p. 193.
- Mustel, E.R. 1962, *Astr. Zh.*, 39, 185.
- Mustel, E.R. 1964, *Soviet Astr.*, 7, 772.
- Mustel, E.R. 1974 in *IAU Symposium 66, Late Stages of Stellar Evolution*, R.J. Tayler and J.E. Hesser, eds., Reidel.
- Mustel, E.R. 1978, *Problems of Physics and Evolution of the Universe*, *Pub. Armenic. Ac.*

- of Sciences, p. 221, 233.
- Mustel, E.R., and Antipova, L.I. 1971, *Nauchn. Inf.*, 19, 32.
- Mustel, E.R., and Antipova, L.I. 1972, *Scient. Inform. Astr. Council USSR*, (Moscow: Academy of Sciences), 19, 32.
- Mustel, E.R., and Baranova, L.I. 1965, *Astr. Zh.*, 42, 42.
- Mustel, E.R., and Baranova, L.I. 1966, *Soviet Astr.*, 43, 488.
- Mustel, E.R., and Boyarchuk, A.A. 1958, *Izv. Krymsk. Astrofiz.*, 20, 86.
- Mustel, E.R., and Boyarchuk, A.A. 1959, *Astr. Zh.*, 36, 762.
- Mustel, E.R., and Boyarchuk, A.A. 1970, *Ap. Space Sci.*, 6, 183.
- Nariai, K. 1974, *Astr. Ap.*, 36, 231.
- Neckel, Th., and Klare, G. 1980, *Astr. Ap. Suppl.*, 42., 251.
- Neff, J.S., Smith, V.V., and Ketelsen, D.A. 1978, *Ap. J. Suppl.*, 38, 89.
- Newton, I. 1713, *Principia Mathematica Philosophiae Naturalis*, second Ed., 3rd book, section 5., p. 541.
- Ney, E.P., and Hatfield, B.F. 1978, *Ap. J.* 219, L111.
- Nussbaumer, H., and Stencel, R.E. 1987, *Exploring the Universe with the IUE Satellite*, ed. Y. Kondo, (Dordrecht, Reidel), p. 203.
- Nussbaumer, H., and Storey, P.J. 1984, *Astr. Ap. Suppl.*, 56, 293.
- Oehler H. 1936, *Z. Astroph.* 12, 281.
- Ogelman, H., Beuermann, K., and Krautter, J. 1984, *Ap. J.*, 287, L31.
- Ogelman, H., Krautter, J., and Beuermann, K. 1987, *Ap. Space Sci.* 130, 279.
- Ogelman, H., Krautter, J., and Beuermann, K. 1987, *Astron. Astroph.* 177, 110.
- Oke, J.B., and Wade, R.A. 1982, *A. J.*, 87, 670.
- Oort, J.H. 1946, *M.N.R.A.S.*, 106, 159.
- Oort, J. 1950, Ed., *IAU Trans. VII*, (Cambridge: Cambridge Univ. Press), p. 305.
- Oort, J.H. 1951, in "Problems of cosmical aerodynamics", Dayton, OH 1951, p. 118.
- Ortolani, S., Rafanelli, P., Rosino, L., and Vittone, A. 1978, *IAU Circ.* 3276.
- Osaki, Y. 1974, *Pub. Astr. Soc. Japan*, 26, 429.
- Oskanyan, A.V. 1983, *IBVS*, No. 2349.
- Osterbrock, D.E. 1974, "Astrophysics of Gaseous Nebulae", (San Francisco: Freeman).
- Pacheco, J.A., and Codina, L.S. 1985, *M.N.R.A.S.* 214, 481.
- Paczynski, B. 1965, *Acta Astr.*, 15, 197.
- Paczynski, B. 1971, *Ann. Rev. Astronom. Astroph.* 9, 183.
- Paczynsky, B., and Sienkiewicz, R. 1972, *Acta astr.*, 22, 73.
- Padin, S., Davis, R.J., and Bode, M.F. 1985, *Nature*, 315, 306.
- Palmer, L.H. and Africano, J.L. 1982, *IBVS*, No. 2069.
- Panek, R.J. 1979, *Ap. J.* 234, 1016.
- Patterson, J. 1978, *Ap. J.*, 225, 954.
- Patterson, J. 1979a, *Ap. J. (Letters)*, 233, L13.
- Patterson, J. 1979b, *Ap. J.*, 231, 789.
- Patterson, J. 1980, *Ap. J.*, 241, 235.
- Patterson, J. 1984, *Ap. J. Suppl.* 54, 443.
- Patterson, J., and Raymond, J.C. 1985a, *Ap. J.*, 292, 535.
- Patterson, J. and Raymond, J.C. 1985b, *Ap. J.* 292, 550.
- Pavlenko, E.P. 1983, *Soviet Astr. Lett.*, 9, 119.
- Payne-Gaposchkin, C. 1957, *Galactic Novae*, Pub. North-Holland.
- Payne-Gaposchkin, C., and Gaposchkin, S. 1942, *Harv. Circ.*, 445.
- Payne-Gaposchkin, C., and Whipple, F.L. 1939, *Harv. Circ.*, 433.
- Payne-Gaposchkin, C., and Menzel, D.H. 1938, *Harv. Circ.*, 428.
- Peimbert, M. and Sarmiento, A. 1984, *Astr. Express*, 1, 97.
- Peltier, L. 1958, *Sky and Telescope*, 17, 555.
- Pettit, E. 1946a, *Publ. A.S.P.*, 58, 159.
- Pettit, E. 1946b, *Publ. A.S.P.*, 58, 255.
- Pettit, E. 1946c, *Publ. A.S.P.*, 58, 359.
- Petterson, J.A. 1979, *IAU Colloquium 53, White Dwarfs and Variable Degenerate Stars*, ed. H.M. Van Horn and V. Weidemann, (Publ. University of Rochester) p. 412.
- Petterson, J.A. 1980, *Ap. J.*, 241, 247.
- Pfau, W. 1976, *Astr. Ap.*, 50, 113.
- Phillips, J.P., and Reay, N.K. 1977, *Astr. Ap.*, 59, 91.
- Piccioni, A., Guarnieri, A., and Bartolini, C. 1984, *Acta Astr.* 34, 473.

- Pickering, E.C. 1905, *Harv. Circ.*, 99.
- Pickering, W.H. 1894, *Astr. Ap.* 13, 201.
- Pirola, V., and Korhonen, T. 1979, *Astr. Ap.*, 79, 254.
- Pike, S.R. 1928, *Proc. Leeds Philos. and Literary Soc.*
- Pike, S.R. 1929, *M.N.R.A.S.*, 89, 538.
- Pilyugin, S.L. 1986, *Astrophysics*, 23, 527.
- Plavec, M., Ulrich, R.K., and Polidan, R.S. 1973, *Pub. A.S.P.*, 85, 769.
- Pogson, R.N., 1908, *Mem. RAS*, 58, 90.
- Popper, D. 1940, *Ap. J.* 92, 262.
- Porcas, R.W., Davis, R.J., and Graham, D.A. 1987, in *RS Ophiuchi (1985) and the Recurrent Nova Phenomenon*, ed. M.F. Bode, (Utrecht: VNU Science Press), p. 203.
- Pottasch, S.R. 1959a, *Ann. Astrophys.*, 22, 297.
- Pottasch, S.R. 1959b, *Ann. Astrophys.*, 22, 310.
- Pottasch, S.R. 1959c, *Ann. Astrophys.*, 22, 318.
- Pottasch, S.R. 1959d, *Ann. Astrophys.*, 22, 394.
- Pottasch, S.R. 1959e, *Ann. Astrophys.*, 22, 412.
- Pottasch, S.R. 1967, *Bull. Astr. Inst. Neth.*, 19, 227.
- Pottasch, S.R. 1985, "Planetary Nebulae" (Reidel Publ. Company).
- Prialnik, D. 1986, *Astrophys. J.*, 310, 222.
- Rafanelli, P., and Rosino, L. 1978, *Astr. Ap. Suppl.*, 31, 337.
- Rahe, J., Boggess, A., Drechsel, H., Holm, A., and Krautter, J. 1980, *Astr. Ap. (Letters)*, 88, L9.
- Raikova, D.V. 1977, *Soviet Astr.*, 21, 30.
- Raymond, J.C., Cox, D.P., and Smith, B.W. 1976, *Ap. J.*, 204, 290.
- Reimers, D. and Cassatella, A. 1985, *Ap. J.*, 297, 275.
- Reynolds, S.P., and Chevalier, R.A. 1984, *Ap. J. (Letters)*, 281, L33.
- Richter, G.A. 1986, *Astr. Nach.*, 307, 221.
- Right, W.H. 1925, *Pub. A.S.P.*, 37, 235.
- Rinsland, C.P., and Wing, R.F. 1982, *Ap. J.* 262, 201.
- Ritter, H. 1987, *Astr. Ap. Suppl.*, 70, 335.
- Robbins, R.R., and Sanyal, A. 1978, *Ap. J.*, 219, 985.
- Robinson, E.L. 1975, *Astr. J.*, 80, 515.
- Robinson, E.L. 1976, *Ann. Review Astr. Ap.*, 14, 119.
- Robinson, E.L., and Nather, R.E. 1977, *Pub. A.S.P.*, 89, 572.
- Robinson, R.L., and Nather, R.E. 1983, *Ap. J.*, 273, 255.
- Robinson, R.L., Nather, R.E., and Kepler, S.O. 1982, *Ap. J.*, 254, 646.
- Robinson, E.L., Nather, R.E., and Patterson, J. 1978, *Ap. J.*, 219, 168.
- Rose, W.K. 1968, *Ap. J.*, 152, 245.
- Rose, W.K., and Smith, R.L. 1972, *Ap. J.*, 172, 699.
- Rosino, L. 1964, *Ann. Ap.*, 50, 113.
- Rosino, L. 1973, *Astr. Ap. Suppl.*, 9, 347.
- Rosino, L. 1987, in *RS Ophiuchi (1985) and the Recurrent Nova Phenomenon*, ed. M.F. Bode (Utrecht: VNU Science Press) p.1.
- Rosino, L., Bianchini, A., and Rafanelli, P. 1982, *Astr. Ap.*, 108, 243.
- Rosino, L., Ciatti, F., and della Valle, M. 1986, *Astr. Ap.*, 158, 34.
- Rosino, L., and Iijima, T. 1987, in *RS Ophiuchi (1985) and the Recurrent Nova Phenomenon*, ed. M.F. Bode, (Utrecht: VNU Science Press), p. 27.
- Rosino, L., and Iijima, T. 1988, *Astr. Ap.* 201, 89.
- Rosino, L., Taffara, S., and Pinto, G. 1960, *Mem. SAIt*, 31, 3.
- Rosino, L., and Tempesti, P. 1977, *Soviet Astr.*, 21, 291.
- Rosseland, S. 1946, *Ap. J.*, 104, 324.
- Rottenberg, J.A. 1952, *M.N.R.A.S.*, 112, 125.
- Ruggles, C.L.N., and Bath, G.T. 1979, *Astr. Ap.*, 80, 97.
- Rush, W.F., and Thompson, R.W. 1977, *Ap. J.*, 211, 184.
- Ruusalepp, M., and Luud, L. 1971, *Tartu Publ.*, 39, 89.
- Sabbadin, F., and Bianchini, A. 1983, *Astr. Ap. Suppl.*, 54, 393.
- Sahade, J., and Wood, F.B. 1978, in "Interacting Binary Stars" (Pergamon Press), p. 114.
- Sandlin, G.D., Brueckner, G.E., and Tousey,

- R. 1977, *Ap. J.* 214, 898
- Sanford, R.F. 1947a, *Publ. A.S.P.*, 59, 87.
- Sanford, R.F. 1947b, *Pub. A.S.P.*, 59, 331.
- Sanford, R.F. 1949, *Ap. J.*, 109, 81.
- Sanyal, A., and Willson, L.A. 1980, *Ap. J.*, 237, 529.
- Saraph, H., and Seaton, M.J. 1980, *M.N.R.A.S.*, 193, 617.
- Sastri, V.K., and Simon, N.R. 1973, *Ap. J.*, 186, 997.
- Sayer, A.R. 1937, *Ann. Harv. Coll. Obs.*, 105, 21.
- Schaefer, B.E., and Patterson, J. 1983, *Ap. J.*, 268, 710.
- Schatzmann, E. 1946, *Ann. Astrophys.*, 9, 199.
- Schatzmann, E. 1949, *Ann. Astrophys.*, 12, 281.
- Schatzmann, E. 1950, *Ann. Astrophys.*, 13, 384.
- Schatzmann, E. 1951, *Ann. Astrophys.*, 14, 305.
- Schatzmann, E. 1958, *Ann. Astrophys.*, 21, 1.
- Schatzmann, E. 1965, in *Stars and Stellar System 8*, eds. L.H. Aller and D.B. McLaughlin, (Chicago: Univ. of Chicago Press), p. 327.
- Scheuer, P.A.G. 1960, *M.N.R.A.S.*, 120, 231.
- Schmidt-Kaler, Th. 1965, (private commun.).
- Schneider, D.P., and Greenstein, J.L. 1979, *Ap. J.*, 233, 935.
- Schoembs, R., and Stolz, B. 1981, *IBVS*, No. 1986.
- Seaquist, E.R., Duric, N., Israel, F.P., Spoelstra, T.A.T., Ulich, B.L., and Gregory, P.C. 1980, *Astr. J.*, 85, 283.
- Seaquist, E.R., and Palimaka, J. 1977, *Ap. J.*, 217, 781.
- Seaton, M.J. 1975, *M.N.R.A.S.* 170, 475.
- Seaton, M.J. 1978 a, *M.N.R.A.S.*, 185, 5P.
- Seaton, M.J. 1978 b, in *Planetary Nebulae: Observations and Theory*, ed. Y. Terzian, p. 131.
- Seaton, M.J. 1979, *M.N.R.A.S.*, 187, 73p.
- Seeliger, H.V. 1892, *Astr. Nachr.*, 130, 393.
- Seeliger, H.V. 1893, *Astr. Nachr.*, 133, 305.
- Seeliger, H.V. 1909, *Astr. Nachr.*, 181, 81.
- Seitter, W.C. 1969, in *IAU Colloquium, Non-Periodic Phenomena in Variable Stars*, ed. L. Detre, (Reidel, Dordrecht), p. 277.
- Seitter, W.C. 1971, in *IAU Colloquium 15*, "Veroff. Remeis Sternw.", Bamberg 9, No. 100, p. 268.
- Seitter, W.C. 1974, *Proc. First European Meeting, Stars and the Milky Way System*, ed. L.N. Mavridis, (Berlin: Springer), 2, p. 39.
- Seitter, W.C. 1985, *ESO Workshop on Production and Distribution of C,N,O Elements*, p. 253.
- Seitter, W.C. 1987, in *RS Ophiuchi (1985) and the Recurrent Nova Phenomenon*, ed. M.F. Bode, (Utrecht: VNU Science Press), p. 63.
- Seitter, W.C., and Duerbeck, H.W. 1987, in *RS Oph (1985) and the Recurrent Nova Phenomenon*, ed. M.F. Bode, (VNU Press, Amsterdam), p. 71.
- Selvelli, P.L. 1982, *Proceed. of Third European IUE Conf. (ESA SP- 176)*, p. 197.
- Selvelli, P.L., and Cassatella, A. 1981, *IAU Colloquium 59, Effects of Mass Loss on Stellar Evolution*, eds. C. Chiosi, and R. Stalio, (Dordrecht, Reidel), p. 515.
- Selvelli, P.L., and Cassatella, A. 1982, *Proceed. of Third European IUE Conf. (ESA SP-170)*, p. 201.
- Selvelli, P.L., Cassatella, A., and Gilmozzi, R. 1990, *Mem. Soc. Astr. Ital.*, 60, 151.
- Selvelli, P.L., Cassatella, A., and Gilmozzi, R. 1990, *The Nature of the Recurrent Nova T CrB*, submitted to *Ap. J.*
- Shaffer, A.W. 1985, in *Cataclysmic Variables and Low Mass X-Ray Binaries*, ed. D.Q. Lamb and T. Patterson, (Reidel Publ. Company), p. 355.
- Shao, C.Y. 1978, *IAU Circ.*, No. 3263.
- Shara, M.M. 1981, *Ap. J.*, 243, 268.
- Shara, M.M., Livio, M., Moffat, A.F.J., and Orio, M. 1986, *Ap. J.* 311, 163.
- Shara, M.M., and Moffat, A.F.J. 1982, *Ap. J. (Letters)*, 258, L41.
- Shara, M.M., and Moffat, A.F.J. 1983, *Ap. J.* 264, 560.
- Shara, M.M., Moffat, A.F.J., Mc Graw, J.T., Dearborn, D.S., Bond, H.E., Kemper, E., and Lamontagne, R. 1984, *Ap. J.*, 282, 763.
- Shara, M.M., Moffat, A.F.J., and Webbink, R.F. 1985, *Ap. J.* 294, 277.
- Shaviv, G. 1987, *Ap. Space Sci.* 130, 303.
- Shaviv, G., and Starrfield, S. 1987, *Ap. J.*

- (Letters), 321, L51.
- Sherrington, M.F., and Jameson, R.F. 1983, M.N.R.A.S., 205, 265.
- Slovak, M.H. 1980, IAU Circ. No. 3493.
- Slovak, M.H. 1981, Ap. J., 248, 1059.
- Smak, J. 1971, Acta Astr., 21, 15.
- Smak, J. 1982, Acta Astr., 32, 213.
- Smak, J. 1987, Proceed. of the Vulcano Workshop 1986: HE-UHE Behaviour of Accreting X-Ray Sources, eds. F. Giovannelli, and G. Mannocchi, (Italian Physical Soc. Conf. Proc. Vol. 8), p.3.
- Snedden, C., and Lambert, D.L., 1975, M.N.R.A.S., 170, 533.
- Snijders, M.A.J. 1987, in RS Ophiuchi (1985) and the Recurrent Nova Phenomenon, ed. M.F. Bode, (Utrecht: VNU Science Press), p. 54.
- Snijders, M.A.J., Batt, T.J., Roche, P.E., Seaton, M.J., Morton, D.C., Spoelstra, T.A.T., and Blades, J.C. 1987, M.N.R.A.S., 228, 329.
- Snijders, M.A.J., Batt, T.J., Seaton, M.J., Blades, J.C., and Morton, D.C. 1984, M.N.R.A.S., 211, 7P.
- Sobolev, V.V. 1960, Moving Envelopes of Stars, (Cambridge: Harvard).
- Sobotka, M., and Grygar, J. 1979, Bull. Astr. Inst. Czechosl., 30, 129.
- Solf, J. 1983, Ap. J., 273, 647.
- Sparks, W.M., 1969 Ap. J. 156, 569.
- Sparks, W.M., and Kutter, G.S. 1987, Ap. J. 321, 394.
- Sparks, W.M., and Starrfield, S. 1973, M.N.R.A.S., 164, 1P.
- Sparks, W.M., Starrfield, S., and Truran, J.W. 1977, in Novae and Related Stars, ed. M. Friedjung, (Dordrecht: Reidel). p.189.
- Sparks, W.M., Starrfield, S., and Truran, J.W. 1978, Ap. J., 220, 1063.
- Sparks, W.M., Starrfield, S., Wyckcoff, S., Williams, R.E., Truran, J.W., and Ney E.P. 1982, NASA CP 2238, p. 478.
- Sparks, W.M., Wu, C.C., Holm, A.V., and Shifter III, F.H. 1980, IAU Highlights of Astronomy, ed. P.A. Wayman, Vol. 5, p. 285.
- Spencer Jones, H. 1931, Annals Cape Obs., 10, No. 9.
- Spoelstra, T.A.T., Taylor, A.R., Pooley, G.G., Evans, A., and Albinson, J.S. 1987, M.N.R.A.S., 224, 791.
- Starrfield, S. 1971a, M.N.R.A.S., 152, 307.
- Starrfield, S. 1971b, M.N.R.A.S., 155, 129.
- Starrfield, S. 1985, in Radiation Hydrodynamics in Stars and Compact Objects, K.H.A. Winkler, ed., Lecture Notes in Physics (Berlin, Springer), p. 255.
- Starrfield, S. 1988, in The Classical Nova, eds. M.F. Bode and A. Evans, (Chichester: Wiley).
- Starrfield, S., and Snijders, M.A.J. 1987, Exploring the Universe with the IUE Satellite, ed. J. Kondo, (Dordrecht, Reidel), p. 377.
- Starrfield, S., and Sparks, W.M. 1987, Ap. Space Sci., 131, 379.
- Starrfield, S., Sparks, W.M., and Truran, J.W. 1985, Ap. J. 291, 136.
- Starrfield, S., Sparks, W.M., and Truran, J.W. 1986 Ap. J. (Letters), 303, L5.
- Starrfield, S., Sparks, W.M., and Williams, R.E. 1982, Advances in UV Astronomy, 4 Years of IUE Research, (NASA C.P. 2238), p. 470.
- Starrfield S.G., Truran, J.W., and Sparks, W.M. 1977 in CNO isotopes in Astrophysics. ed. J. Audouze, p. 49.
- Starrfield, S., Truran, J.W., and Sparks, W.M. 1978, Ap. J. 226, 186.
- Steffl, S., and Grygar, J. 1981, Bull. Astr. Inst. Czechosl., 33, 116.
- Steinle, H., and Pietsch, W. 1987, Ap. Space Sci., 131, 485.
- Stephenson, C.B. 1967, Pub. A.S.P., 79, 584.
- Stephenson, C.B., and Herr, R.B. 1963, Pub. A.S.P., 75, 253.
- Stickland, D.J. 1983, Astrophy. Sp. Sci. 92, 197.
- Stickland, D.J., Penn, C.J., Seaton, M.J., Snijders, M.A.J., Storey, P.J. and C.R. Kitchin, 1979 in The first year of IUE, p.63 ed. A.J. Willis.
- Stickland, D.J., Penn, C.J., Seaton, M.J., Snijders, M.A.J., and Storey, P.J. 1981, M.N.R.A.S., 195, 27p.
- Storey, P.J. 1981, M.M.R.A.S. 195, 27P.
- Stoy, R.H. 1933, M.N.R.A.S., 93, 588.
- Stratton, F.J.M. 1928, in Handbuch der Astrophysik 6, 251.

- Stratton, F.J.M. 1936, M.N.R.A.S., 96, 373.
- Stratton, F.J.M. 1945, M.N.R.A.S., 105, 275.
- Stratton, F.J.M., and Manning, W.H. 1934, Atlas of Spectra of Nova Herculis, 1939, The Solar Physics (Observatory: Cambridge, Eveyland).
- Strecker, D.W., Erickson, E.F., and Witteborn, F.C. 1979, Ap. J. Suppl., 41, 501.
- Strittmatter, P.A., Woolf, N.J., Thompson, R.I., Wilkerson, S., Angel, J.R.P., Stockman, H.S., Gilbert, G., Grandi, S.A., Larson, H., and Fink, U. 1977, Ap. J. 216, 23.
- Struve, O. 1947, Science, 106, 149.
- Struve, O. 1955, Sky Telesc., 14, 275.
- Svolopoulos, S.N. 1966, Pub. A.S.P., 78, 157.
- Swings, P. and Struve, O. 1941, Ap. J., 94, 291.
- Swings, P. and Struve, O. 1943, Ap. J., 98, 91.
- Szkody, P. 1977, Ap. J., 217, 140.
- Szkody, P. 1985, in "Cataclysmic Variables and Low-Mass X-Ray Binaries", ed. D.Q. Lamb and J. Patterson, (Reidel Publ. Company), p. 385.
- Szkody, P., Mattei, J.A., and Mateo, M. 1985, Pub. A.S.P., 97, 264.
- Takalo, L.O., and Nousek, J.A. 1985, Publ.A.S.P. 97,570
- Tempesti, P. 1975, IAU Circ. No. 2834.
- Tempesti, P. 1979, Astr. Nach., 300, 51.
- Thomas, H.L. 1940, Harv. Bull., 912, 11.
- Tolbert, C.R., Pecker, J.C., and Pottasch, S.R. 1967, BAN, 19, 17.
- Truran, J.W. 1985, Nucleosynthesis: Challenges and new Developments, eds. W.D. Arnett, and J.W. Truran, Univ. of Chicago press. (Chicago).
- Truran, J.W., Livio, M., Hayes, J., Starrfield, S., Sparks, W.M. 1988, Ap. J. 324, 345.
- Turolla, R., Nobili, L., and Calvani, M. 1988, Ap. J., 324, 899.
- Tylenda, R. 1977, Acta Astr., 27, 389.
- Tylenda, R. 1978, Acta Astr., 28, 333.
- Tylenda, R. 1979, Acta Astr., 29, 55.
- Unsöld, A. 1930, Zs. Astrophys., 1, 138.
- Van den Bergh, S., and Pritchett, C.J. 1986, Pub. A.S.P., 98, 110.
- Van den Bergh, S., and YOUNGH, P.F. 1987, Astr. Ap. Suppl., 70, 125.
- Van Houten, C.J. 1966, B.A.N., 18, 439.
- de Vaucouleurs, G. 1978, Ap. J., 223, 351.
- Verbunt, F. 1987, Astr. Ap. Suppl. Series, 71, 339.
- Verbunt, F., and Wade, R.A. 1984, Astr. Ap. Suppl., 57, 193.
- Vidal, N.V., and Rodgers, A.W. 1974, Pub. A.S.P., 86, 26.
- Viotti, R., Altamore, A., Baratta, G.B., Cassatella, A, and Freidjung, M. 1984, Ap. J., 283, 226.
- Vogel, H.C. 1893, Abh. Konigl. Preuss. Akad. Wiss. Berlin.
- Vogt, N. 1975, Astr. Ap., 41, 15.
- Vogt, N. 1976, in IAU Symposium No. 73, Structure and Evolution of Close Binaries, Eds. P. Eggleton, S. Mitton, and J. Whelau (Dordrecht:Reidel), p. 147.
- Vogt, N. 1981, Mitt. Astr. Ges., 57, 79.
- Voloshina, I.B., and Doroshenko, V.T. 1977, Soviet Astr., 21, 313.
- Vorontsov-Velyaminov, B.A. 1940, Byull. Inst. Sternberg. Moskva, No. 1.
- Vorontsov-Velyaminov, B.A. 1948, "Gasovye tumannosti i novye zvezdy" (Moskva-Leningrad: Izd. Akad. Nauk).
- Vorontsov-Velyaminov, B.A. 1953, "Gasnebel und Neue Sterne" (Berlin: Kultur und Fortschritt).
- Wade, R.A. 1984, M.N.R.A.S., 208, 381.
- Wade, R.A. 1985, in "Interacting Binaries", ed. P.P Eggleton and J.E. Pringle, (Reidel Publ. Company), p. 289.
- Wagner, R.L., Gull, R.G., Byrd, G.G., and Loren, R.B. 1971, Ap. J., 165, 431.
- Walborn, N.R. 1971, Pub. A.S.P., 83, 813.
- Walker, A.R. 1977, M.N.R.A.S., 179, 587.
- Walker, M.F. 1954, Pub. A.S.P., 66, 230.
- Walker, M.F. 1956, Ap. J., 123, 68.
- Walker, M.F. 1957 in IAU Symposium 3, Non-Stable Stars, ed. G.H. Herbig, (Cambridge: Univ. Press.), p. 46.
- Walker, M.F. 1963, Ap. J., 138, 313.
- Wallerstein, G. 1958, Pub. A.S.P., 70, 537.
- Wallerstein, G. 1963, Pub. A.S.P., 75, 26.
- Wallerstein, G., and Garnavich, P.M. 1986, Pub. A.S.P., 98, 875.
- Wargau, W., Drechsel, H., and Rahe, J. 1982, Proc. 3 European IUE Conference ESA S.P., 176, p. 215.

- Wargau, W., Drechsel, H., and Rahe, J. 1983, *Acta Astr.*, 33, 149.
- Warner, B. 1971, *Pub. A.S.P.*, 83, 817.
- Warner, B. 1972, *M.N.R.A.S.*, 160, 35P.
- Warner, B. 1976 in *IAU Symposium No 73, Structure and Evolution of Close Binary Systems*, Eds. P.Eggleton, S.Mitton, and J.Whelau (Dordrecht:Reidel) p. 85.
- Warner, B. 1981, *M.N.R.A.S.*, 195, 101.
- Warner, B. 1985 a, *Proced. ESA Workshop, "Recent Results on Cataclysmic Variables"*, ESA S.P., 236, 1.
- Warner, B. 1985 b, *M.N.R.A.S.*, 217, 1P.
- Warner, B. 1986a, *M.N.R.A.S.*, 219, 751.
- Warner, B. 1986b, *Ap. Space Sci.*, 118, 271.
- Warner, B. 1986c, *M.N.R.A.S.*, 222, 11.
- Warner, B. 1987a, *M.N.R.A.S.*, 212, 917.
- Warner, B. 1987b, *M.N.R.A.S.*, 227, 23.
- Warner, B., and Livio, M. 1987, *Ap. J. (Letters)*, 322, 95L.
- Watson, M.G., King, A.R., and Osborne, J. 1985, *M.N.R.A.S.*, 212, 917.
- Watson, R. 1925, *Harvard Bull.* 820.
- Weaver, H.F. 1951, *Ap. J.*, 113, 320.
- Weaver, H.F. 1974, *IAU Highlights of Astronomy*, ed. G. Contopoulos, (Dordrecht: Reidel), 3, 509.
- Webbink, R.F. 1976, *Nature*, 262, 271.
- Webbink, R., Livio, M., Truran, J.W. and Orio, M. 1987, *Ap.J.*, 314, 653.
- Wendker, H.J. 1978, *Catalogue of Radio Stars*, (preprint).
- Whipple, F.L., and Payne-Gaposchkin, C. 1936, *Harv. Circ.* 413.
- Whipple, F.L., and Payne-Gaposchkin, C. 1937, *Harv. Circ.* 414.
- White, R.L. 1985, *Radio Stars*, eds. R.M. Hjellming, and D.M. Gibson, (Dordrecht, Reidel), p. 45.
- Whitelock, P.A., Carter, B.S., Feast, M.W., Glass, I.S., Laney, D., Menzies, J.W., Walsh, J.W., and Williams, P.M. 1984, *M.N.R.A.S.*, 211, 421.
- Williams, G. 1983, *Ap. J. Suppl.*, 53, 523.
- Williams, R.E. 1977, in *IAU Colloquium 42, The Interaction of Variable Stars with Their Environment*, ed. R. Kippenhahn, J. Rahe, and W. Strohmeier (Bamberg: Schadel) p. 242.
- Williams, R.E. 1982, *Ap. J.*, 261, 170.
- Williams, R.E., and Ferguson, D.H. 1983, in *IAU Colloquium 72, Cataclysmic Variables and Related Objects*, eds. M. Livio and G. Shaviv, (Dordrecht:Reidel), p. 97.
- Williams, R.E., and Gallagher, J.S. 1979, *Ap. J.* 228, 482.
- Williams, R.E., Ney, E.P., Sparks, W.M., Starrfield, S.G., Wyckoff, S., and Truran, J.W. 1985, *M.N.R.A.S.*, 212, 753.
- Williams, R.E., Sparks, W.M., Gallagher, J.S., Ney, E.P., Starrfield, S.G., and Truran, J.W. 1981, *Ap. J.*, 251, 221.
- Williams, R.E., Woolf, N.J., Hege, E.K., Moore, R.L., and Kopriva, D.A. 1978, *Ap. J.*, 224, 171.
- Willis, A.J., and Garmany, C.D. 1987, in *Exploring the Universe with the IUE Satellite*, ed. Y. Kondo, (Dordrecht: Reidel).
- Wilson, R. 1935, *Ap. J.*, 82, 233.
- Wolf, B. 1977, *IAU Colloquium No 42, The Interaction of Variable Stars with Their Environment*, ed. R. Kippenhahn, J. Rahe, and W. Strohmeier, (Bamberg) p. 151.
- Woszczyk, A., Smolinski, J., Maron, N., Strobel, A., and Krempec, J. 1968, *Ap. Space Sci.*, 1, 264.
- Wright, W.H. 1919, *Lick Obs. Bull.*, 10, 30.
- Wu, C.C., Boggess, A., Holm, A.V., Perri, P.M., Schiffer, F.H., III, Turnrose, B.E. and West, D.K. 1978, *Bull. Am. Astr. Soc.*, 10, 687.
- Wu, C.C., and Kester, Do 1977, *Astr. Ap.*, 58, 331.
- Wychoff, S., and Wehinger, P.A. 1977, *Proceed. IAU Colloquium 42*, eds. R. Kippenhahn, J. Rahe, and W. Strohmeier, (Bamberg, Sept. 6-9), p.201.
- Wyse, A.B., 1939, *Lick Pub.*, 14, 93.
- Wyse, A.B. 1940, *Publ. A.S.P.* 52, 334.
- Yamashita, Y. 1968, *Pub. Astr. Soc. Japan*, 20, 183.
- Yamashita, Y. 1975, *Ann. Tokyo Astr. Obs.* 2nd Ser., 15, 1.
- Young, P., and Schneider, D.P. 1980, *Ap.J.* 238, 955.
- Zanstra, H. 1931, *Pub. Dom. Ap. Obs.*, 4, 209.
- Zollner, J.C.F. 1865, *Photometrische Untersuchungen*, Leipzig, p. 241.
- Zwicky, F. 1956, *Astr. J.*, 61, 328.

PART III

SYMBIOTIC STARS

Written by
Michael Friedjung
Roberto Viotti

